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THE PRESSURE DEPENDENCE OF ACOUSTIC VELOCITY AND QUALITY FACTOR – NEW PETROPHYSICAL MODELS

M. DOBRÓKA[1,2], J. SOMOGYI MOLNÁR[1]

[1]University of Miskolc, Department of Geophysics, 3515 Miskolc-Egyetemváros, Hungary
e-mail: dobroka@uni-miskolc.hu
[2]MTA-ME Applied Geosciences Research Group, 3515 Miskolc-Egyetemváros, Hungary

In this study we introduce new rock physical models which describe the pressure dependence of seismic velocity and quality factor. The models are based on the idea (accepted in the literature) that microcracks in rocks are opened and closed under the change of pressure. The models were applied to acoustic P wave velocity data measured on core samples originated from oil-drilling wells (27 samples) and also seismic velocity and quality factor data sets published in international literature. During the measurements the pulse transmission and the spectral ratio techniques were used. Measurements were carried out at various incremental pressures and parameters of the models were determined by linearized inversion methods. The calculated data matched accurately with measured data proving that the new rock physical models apply well in practice.

Keywords: pressure; acoustic velocity; quality factor; petrophysical model; microcrack.

1. Introduction

The characteristics of propagation of seismic wave carry information about important mechanical properties of rocks. Therefore the determination of velocity and attenuation of acoustic wave is a frequent task in the laboratory. The velocity of acoustic waves propagating in different rocks under various confining pressure values (Wyllie et al. 1958; Stacey 1976; King 2009) and also under different pore pressures (Nur and Simmons 1969; Darot and Reuschlé 2000; He and Schmitt 2006) were investigated for several decades by many researchers. The phenomenon that the wave velocity is increasing because of increasing pressure is well-known and was explained on various rock mechanical studies (Wyllie et al. 1956, Birch 1960). One of the most frequently used mechanisms for explaining the phenomenon is based on the closure of microcracks in rocks under pressure (Best 1997; Hassan and Vega 2009; Sengun et al. 2011). Singh et al. (2006) created an empirical model for the pressure dependent wave velocity after observing measured P and S wave propagation velocities on several sandstone samples. Several petrophysical models are known in the literature, e.g., Biot model (Biot 1956a,b), Gassmann model (Gassmann 1951), Contact radius model (CRM) (Duffy and Mindlin 1957), Friction model (FM) (Winkler and Nur 1982; Stewart et al. 1983), etc. These models provide proper approach for the description of the phenomena depending on the type of rock.

Seismic wave attenuation in rocks is usually explained by the nonlinear friction model, the Biot model, viscoelastic models, and elastic scattering. The frictional model predicts a parameter quality factor (Q) that is dependent on amplitude (Mavko et al. 1979). The Biot (1956a,b) model predicts the existence of "poroelastic" attenuation due to the relative motion between solid and liquid in saturated rocks. The viscoelastic model (Bland 1960) contains numerous physical mechanisms, viz. "squirt" or "squish" flow (Mavko and Jizba 1991), mechanical defects of rocks such as anelasticity of cracks (Lucet et al. 1991), grain-scale local flow (Mavko and Jizba 1991), and viscous relaxation (Jones 1986). Attenuation predicted by the elastic scattering mechanism depends on the ratio of seismic wavelength to the diameter of the inhomogeneities (Sayers 1981). Laboratory measurements of attenuation have been made at seismic wave frequencies (Spencer 1981; Dunn 1987), sonic wave frequencies (Murphy 1982; Lucet et al. 1991) and more commonly at ultrasonic wave frequencies (Toksöz et al. 1979; Winkler 1985). Measurements made under different pressure conditions are useful for understanding the mechanisms of attenuation. The velocities of P and S waves propagating in dry, water-, brine-, methane-saturated and frozen samples under pressure were measured by Toksöz et al. (1979) for studying their attenuations. He found that the attenuation was higher in case of water-, brine-saturated samples than that of methane-saturated and dry samples and the attenuation decreased with increasing pressure. The reason of this phenomenon is the closure of microcracks under varying pressure according to Johnston et al. (1979), Yu et al. (1993), Best (1997).

To reasonably interpret laboratory measurements, a quantitative model of the mechanism of pressure dependence of seismic velocity and quality factor is required. In this paper petrophysical models obeying to the theory of closure of microcracks in rocks under pressure are presented.

2. The pressure dependent acoustic velocity model

Phenomena of the material world are so complex that cannot be described in their entirety. Hence we consider the most important and most essential properties and neglecting the rest of all (in other aspects may be important) characteristics we set up a model. In the model we simplify the studied structure and henceforth we talk about the properties of the model. This approach was followed at the development of our rock physical models, which describe the stress dependence of the absorption-dispersion characteristics of acoustic waves under uniaxial stress.

A general observation is that the pore volume reduces by increasing pressure, thus an increasing wave velocity can be measured (Birch 1960). Brace and Walsh (1964) explained this phenomenon by closure of microcracks. For this reason we introduce parameter N as a number of open microcracks. The developed velocity model is valid only in the elastic (reversible) range. (Reaching a critical pressure (Anselmetti and Eberli 1997) the reversible range is exceeded and new microcracks open due to destruction of the sample, hence increasing velocity is observed.) At the development of the model we restricted ourselves to uniaxial stress state and longitudinal acoustic waves.

If we create a $d\sigma$ stress increase in the rock, we find that dN (the change of the number of open microcracks) is directly proportional to the applied $d\sigma$ stress increase. At the same time dN is directly proportional to N. We can unify both assumptions in the following differential equation

$$dN = -\lambda N \, d\sigma \,, \qquad (1)$$

where λ is new material quality dependent petrophysical constant. In Eq. (1) the negative sign represents that at increasing stress - with closing microcracks - the number of the open microcracks decreases. The solution of the upper equation is

$$N = N_0 e^{-\lambda\sigma} \,, \qquad (2)$$

where N_0 is the number of open microcracks at stress-free state ($\sigma = 0$). We assume also a linear relationship between the change of the propagation velocity - due to stress increase - dv and dN

$$dv = -\alpha \, dN \, , \tag{3}$$

where proportionality factor α is a material quality dependent constant. The negative sign represents that the velocity increases with decreasing number of cracks. Combining Eq. (3) with Eqs. (1-2) we obtain

$$dv = \alpha \lambda N_0 e^{-\lambda\sigma} \, d\sigma \, . \tag{4}$$

After integrating Eq. (4) we have

$$v = K - \alpha N_0 e^{-\lambda\sigma} \, . \tag{5}$$

At stress-free state ($\sigma = 0$) the propagation velocity v_0 can be measured, which can also be calculated from Eq. (5) by $v_0 = K - \alpha N_0$. From here we get the integration constant: $K = v_0 + \alpha N_0$. With this result and the introduction of $\Delta v = \alpha N_0$, Eq. (5) can be rewritten in the following form

$$v = v_0 + \Delta v (1 - e^{-\lambda\sigma}) , \tag{6}$$

where λ is a new (stress-independent) petrophysical constant, of which physical meaning is necessary to be given. Introducing the notation $u = v_{max} - v$, wherewith Eq. (6) can be written in the form

$$u = \Delta v \, e^{-\lambda\sigma} \, . \tag{7}$$

It can be seen that at the characteristic stress σ^* (when $\lambda\sigma^*=1$) the quantity v_{max}-v decreases from its „initial" value Δv to $\Delta v/e$. The petrophysical characteristic λ is the reciprocal value of σ^*. On the other hand, we can also give another meaning of parameter λ: velocity response of rocks may be different to the same amount of change in rock pressure, or in other words, the pressure sensitivity of measured velocity is different. The parameter sensitivity functions are extensively used in the seismic (Dobróka 1987, 1988), the geoelectric (Gyulai 1989), electromagnetic (Szalai and Szarka 2008) and well-logging (Dobróka and Szabó 2011) literature. We introduce the (logarithmic) stress sensitivity of the $u=v_{max}$-v velocity as

$$S(\sigma) = -\frac{1}{u}\frac{du}{d\sigma} = -\frac{d \ln(u)}{d\sigma} \, . \tag{8}$$

Using Eq. (7) it can be seen that

$$\lambda = -\frac{d \ln(u)}{d\sigma} = S \, , \tag{9}$$

which shows that the petrophysical characteristic λ is the logarithmic stress sensitivity of the $u=v_{max}$-v velocity. It can be seen that in our petrophysical model the logarithmic stress sensitivity is independent of stress.

Eq. (6) provides a theoretical connection between the propagation velocity and rock pressure. The model equation contains three model parameters (v_0, Δv, λ) which are to be determined by using measured velocity data sets. Eq. (6) shows that the propagation velocity - as a function of stress - starts from v_0 and increases up to the $v_{max} = v_0 + \Delta v$ value according to the function $1-exp(-\lambda\sigma)$. Consequently, the velocity reaches to a limit v_{max} at high stress values. The value $\Delta v = v_{max} - v_0$ gives a velocity range in which the propagation velocity varies from stress-free state up to the state characterized by high rock pressure. In the range of high stresses new microcracks can arise in the rock, thus the description of the parameters is only valid in the framework of the model assumptions (it means linear- or reversible range). It can be mentioned that the description of non-reversible range was not a goal in this paper.

3. The pressure dependent quality factor model

The effect of microcracks for quality factor - like in case of propagation velocity - can be studied based on qualitative considerations, without detailed analysis of the structure and the physical mechanisms. It is obvious that change dN leads to a change dQ in the quality factor. We assume again a linear relationship between them and write

$$dQ = -\beta dN , \qquad (10)$$

where β is another proportionality factor (material quality dependent constant). The negative sign represents that the quality factor is increasing with closing microcracks. Combining Eq. (10) with Eqs. (1-2) the following equation is obtained

$$dQ = \beta \lambda N_o e^{-\lambda \delta} d\sigma . \qquad (11)$$

Solving Eq. (11) and introducing the notation $\Delta Q = \beta N_0$, we have the following model equation similarly to Eq. (6)

$$Q = Q_o + \Delta Q\left(1 - e^{-\lambda\sigma}\right), \qquad (12)$$

where Q_0 is the quality factor at stress-free state ($\sigma = 0$) and λ is the common proportionality factor (material characteristic) appearing in Eq. (6) and Eq. (12). It is well-known that there can be several reasons to absorption. Using Eq. (12) we describe the attenuation caused by only the change in the number of microcracks under varying pressure. The model contains three parameters (Q_0, ΔQ, λ), which can be determined by the inversion of measured data sets.

4. Case studies for the velocity model

The pressure dependent velocity model was tested on longitudinal wave velocity data sets. The pulse transmission technique was used for P wave velocity measurements. The measurements required special measuring equipment which was compiled at the Department of Geophysics (University of Miskolc). The pulse generator emitted a positive voltage pulse of about 250 volts for a duration 2 μs to the piezoelectric transmitter crystal which started an acoustic wave in the sample. The sensors of the transmitter and the receiver were piezoelectric ceramic disks made of barium titanate. The receiver crystal transformed the acoustic sign to electric pulse which was amplified by a broadband differential amplifier. We used 66dB amplification in the frequency range 1-300kHz. A pulse - the trigger - was emitted also by the pulse generator which synchronized the measurement system and actuated the high-frequency digital oscilloscope. In order to increase the signal-to-noise ratio a 32-fold vertical summary was applied thus picking the first arrivals were more accurate. By means of the oscilloscope picture, the arrival time of waves were detected, thus, propagation times were measured. Propagation velocity of acoustic waves can be determined by means of that of travel times and length of sample.

We performed wave velocity measurements on 27 different sandstone samples originated from oil-drilling wells. Two typical test results (Sample-1 and Sample-2) are presented in the paper. Sample-1 was a fine-, medium-grained sandstone while Sample-2 was a coarse-grained pebbly sandstone. Rock samples subjected to uniaxial stress were analyzed with an electromechanical pressing device and wave velocities - as a function of pressure - were measured at adjoining pressures (up to 20MPa). We obtained that the longitudinal velocity increased with increasing pressure. In order not to exceed the reversible range and to avoid creating new cracks, samples were loaded during our measurements only up to one third of the critical uniaxial strength.

An important question is that how reproducible the measurements are. Hence we repeated the measurements in case of several samples. Measurement data of Sample A is presented in Fig. 1. It was shown that the second measurement provided the same result with very good approximation. Thus the phenomenon is highly reproducible and new microcracks were not formed during the measurements, thus the reversible range was not exceeded.

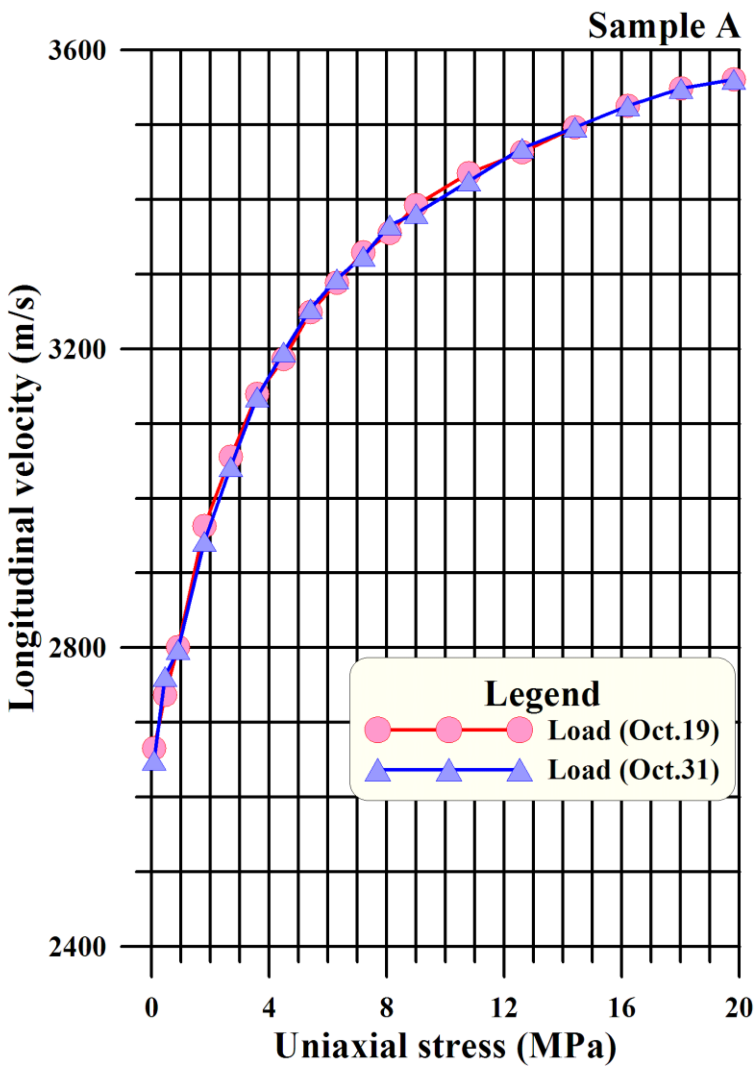


Fig. 1. Result of repeated measurements for studying reproducibility

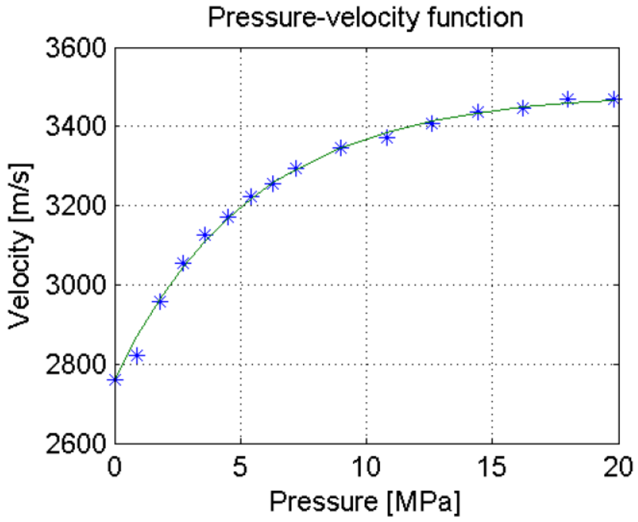
As it was mentioned we processed also independent data sets - chosen from literature - measured on Berea and Lyons samples to confirm the reliability of the velocity model. The Berea medium-grained sandstone sample (Toksöz et al. 1979) was composed of angular grains showing microcracks and the grain contacts were somewhat jagged and were weakly cemented. It had an average porosity of 16 %, permeability of 75 mD, and a bulk density of 2.61 g/cm^3. The Lyons sample (Xu et al. 2006) was a low-porosity, Permian aeolian deposit composed of mostly well-sorted quartz grains (90%) with less than 3% clay content. The Lyons sandstone was composed of rounded grains with a grain size of about 0.2 mm cemented well. The grains showed numerous microcracks along the grain boundaries.

In order to prove the validity and practical applicability of the velocity model introduced in Section 2, we present the interpretation of measurement data of the described samples. The established velocity model makes the possibility to calculate the propagation velocity at any pressure based on known parameters (v_0, Δv, λ) of a rock. The parameters appearing in the model equation can be determined by processing measurement data based on geophysical inversion methods (Dobróka et al. 1991). Since the relevant data sets contained relatively low amount of noise and the problem was overdetermined, the Gaussian Least Squares Method was used (Menke, 1984). The inversion results for each sample can be seen in Table I.

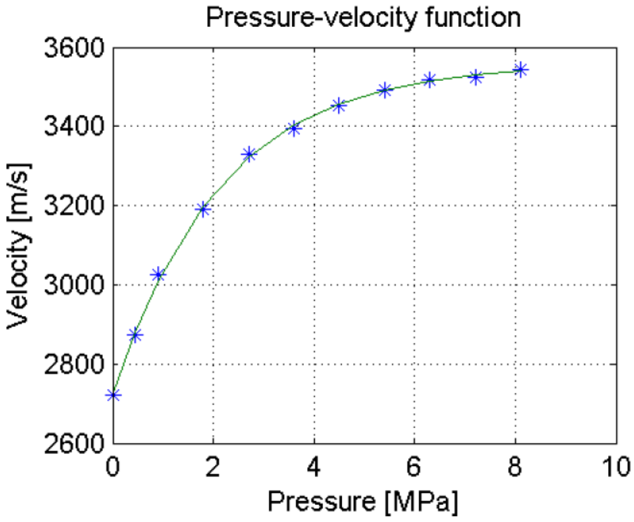
Table I. Model parameters estimated by linearized inversion using the developed velocity model

Sample	v_0 (m/s)	Δv (m/s)	λ (1/MPa)
Sample 1	2761,5	724,9	0,1826
Sample 2	2722,5	835,6	0,4677
Berea sample (Toksöz et al. 1979)	3324,9	825,2	0,1341
Lyons sample (Xu et al. 2006)	3944,4	784,7	0,1069

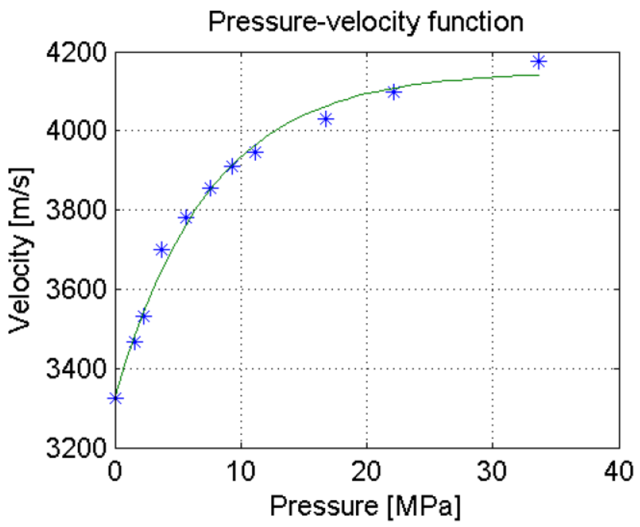
With the estimated parameters the velocities can be calculated at any pressure by substituting them into Eq. (6). The results are shown in Figs. 2-5, where the solid line shows the calculated velocity-pressure function while symbols represent the measured data.



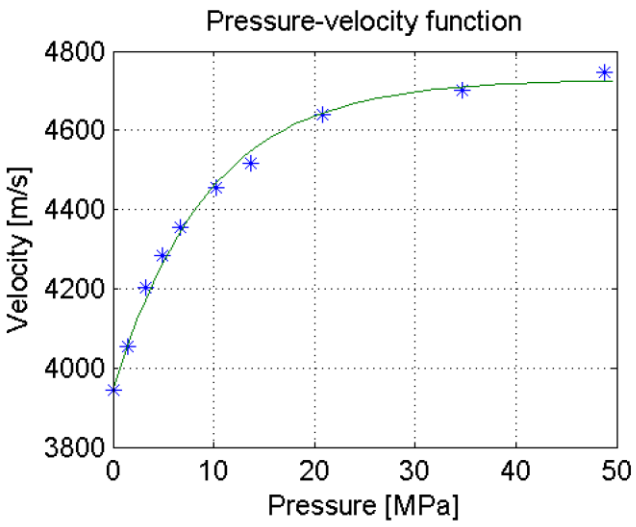
Figs. 2. Pressure dependence of longitudinal wave velocity on Sample 1 (solid line – calculated data produced by the velocity model, asterisks – measured data).



Figs. 3. Pressure dependence of longitudinal wave velocity on Sample 2 (solid line – calculated data produced by the velocity model, asterisks – measured data).



Figs. 4. Pressure dependence of longitudinal wave velocity on Berea sample (solid line – calculated data produced by the velocity model, asterisks – measured data). Data obtained from Toksöz et al. (1979).



Figs. 5. Pressure dependence of longitudinal wave velocity on Lyons sample (solid line – calculated data produced by the velocity model, asterisks – measured data). Data obtained from Xu et al. (2006).

The figures show that the calculated curves are in good accordance with the measured data proving that the petrophysical model in Eq. (6) applies well in practice. It can also be seen that in the lower pressure region, the increase in velocity with increasing pressure is very steep and nonlinear; this is due to the closure of microcracks. In the higher pressure domain, the increase in velocity (with increasing pressure) is moderate as fewer number of cracks are closed. The model was applied with success on further 25 sandstone samples (fine-, medium-, coarse-grained, pebbly, tuffy etc.) during the research.

5. Case studies for the quality factor model

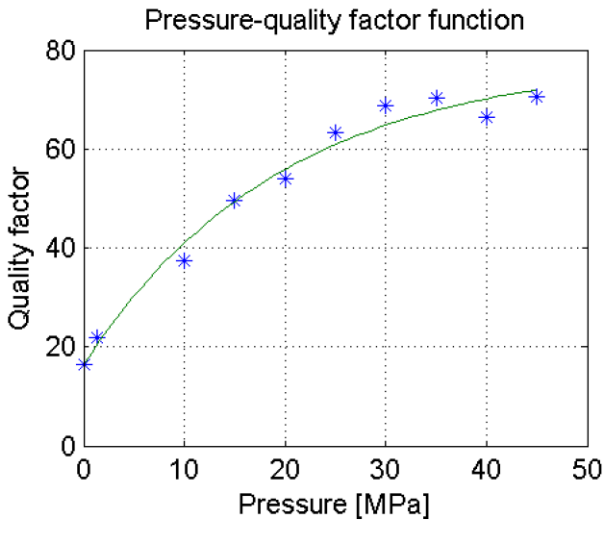
The quality factor model was tested on measurement data published in literature. Data sets measured on Berea (Prasad and Manghnani 1997) and a sample marked with V175 (Best 1997) were processed. The analyzed Berea sandstone sample was composed of angular grains (150–200 μm) which showed microcracks. The grain contacts were somewhat jagged and were weakly cemented. The spectral ratios technique was used for quality factor measurements (Toksöz et al. 1979). Sandstone sample marked with V175 was taken from depth 175m and had abundant secondary porosity. A single-frequency pulse-echo system was used to measure P wave attenuation (Winkler and Plona 1982). The accuracy of the measurement was ±0,3%.

The same linearized geophysical inversion method was used for the interpretation of measurement data. Table II. shows the inversion results for both samples, respectively.

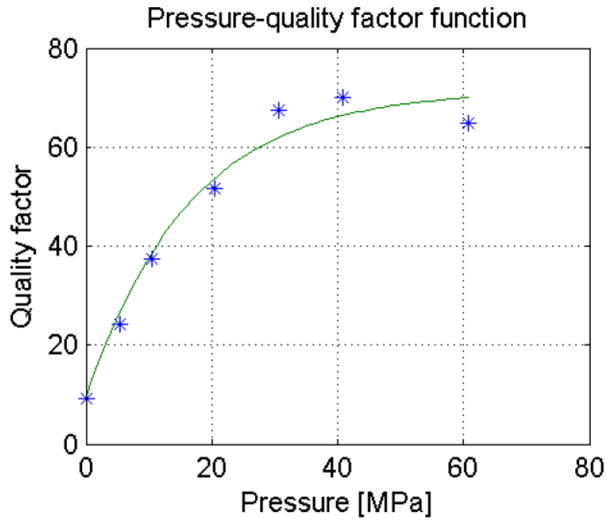
Table II. Model parameters estimated by linearized inversion using the developed quality factor model

Sample	Q_0 (m/s)	ΔQ (m/s)	λ (1/MPa)
Berea sample (Prasad and Manghnani 1997)	27,25	61,82	0,0507
Sample marked with V175 (Best 1997)	9,26	62,24	0,0612

Hence with the estimated parameters the quality factors can be determined at any pressure by means of the developed model equation. Figs. 6-7 represent the results. The sandstone samples show significant increase in quality factor with pressure, which can be attributed to the presence of microcracks within the samples (the number of open microcracks reduces as the pressure is increased). The relatively small change in quality factor over approximately 20MPa implies that most of the cracks are closed.



Figs. 6. Quality factor-pressure function on Berea sample (solid line – calculated data produced by the quality factor model, asterisks – measured data). Data obtained from Prasad and Manghnani (1997).



Figs. 7. Quality factor-pressure function on sample marked with V175 (solid line – calculated data produced by the quality factor model, asterisks – measured data). Data obtained from Best (1997).

For the characterization of the accuracy of inversion estimates, the measure of fitting in data space was calculated according to the data misfit (*D[%])* suggested by Dobróka *et al.* 1991

$$D = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(\frac{d_k^{(m)} - d_k^{(c)}}{d_k^{(c)}}\right)^2} \cdot 100\ [\%]\ , \tag{13}$$

where $d_k^{(m)}$ is the measured velocity/quality factor at the k-th pressure and $d_k^{(c)}$ is the k-th calculated velocity/quality factor data, which can be computed by Eq. (6) and Eq. (12). Table III. contains the value of data misfits for each sample at the end of the inversion procedure.

Table III. Values of the calculated measure of fitting in data space according to the data misfit formula

Sample	**D (%)**
Sample 1	0,28
Sample 2	0,22
Berea sample (Toksöz et al. 1979)	0,61
Lyons sample (Xu et al. 2006)	0,38
Berea sample (Prasad and Manghnani 1997)	4,8
Sample marked with V175 (Best 1997)	6,75

The fitting in the case of processed velocity data sets was under 1%. But in case of quality factor measurement data it was 4,8% and 6,75%, respectively. It can be originated in that quality factors had been measured just beside at few pressure values. The inversion would have been more accurate – resulting in smaller data misfit – if the number of measurement data had been more. These results confirm the accuracy of the inversion estimates and the feasibility of the developed petrophysical models.

Conclusions

We presented new petrophysical models for describing the connection between the propagation velocity of acoustic wave and rock pressure as well as quality factor and pressure. The models (valid only in reversible/elastic range) are based on the idea that microcracks are opened and closed under the change of pressure. Within the confines of the models, differential equations were set up describing the phenomenon of pressure dependence. As it was shown, both seismic velocity and quality factor increase with increasing pressure. The rate of increase is high at low pressures and levels off at higher pressures which can be attributed to the closure of microcracks.

The suggested models were applied to acoustic velocity data measured on core samples and also seismic velocity and quality factor data sets chosen from the literature. By means of inversion-based data processing, the model parameters were determined from measurement data, thus, calculated data could be produced by the implementation of the petrophysical models in the forward problem. The inverse problem was significantly overdetermined; hence the inversion procedure was numerically stable and could be handled by a linear inversion technique. The calculated data match accurately with measured data proving that the petrophysical models apply well in practice. As it was shown the noise in data space was small-scale, which supports the reliability of the inversion results and the accuracy, feasibility of the developed petrophysical models. In our petrophysical model the λ logarithmic stress sensitivity of the propagation velocity was introduced as a new material characteristic.

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