Effects of Porestructure on Sonic Velocity in Carbonates

Ralf J. Weger^{*1}, Gregor T. Baechle¹, Jose Luis Masafarro², and Gregor P. Eberli¹

¹ Comparative Sedimentology Laboratory,

University of Miami, 4600 Rickenbacker Cswy, Miami, FL 33149

² Shell International E&P, Carbonate Development Team, Volmerlaan 8, 2280 AB Rijswijk, The Netherlands

Summary

The presence of round pores generally causes a positive deviation from Wyllie's equation (Anselmetti and Eberli 1993, 1999; Saleh and Castagna 2004). However, carbonates contain a large number of different pore types that are not related roundness alone. Three quantitative pore shape parameters derived from digital image analysis are introduced to capture the complicated pore structure of carbonates with the goal to enhance porosity prediction from velocity. The first parameter that describes the roundness of the pores was first introduced by Anselmetti et al. (1998) and called γ . The second parameter Perimeter-over-Area (PoA) captures the overall tortuosity of the pores system. The third parameter, Dominant Poresize, is a measure of the dominant pore size within the thin section. Out of these three parameters, PoA is the most dominant factor controlling velocity at a given porosity with Dominant Poresize being second, while roundness alone is the least important factor of the three. We conclude that the roundness of individual pores is not as relevant as the simplicity of the pore system, i.e., the pore system with low tortuosity. Combining all three parameters and porosity in a multivariate linear regression increases correlation to velocity from R^2 of 0.49 (porosity alone) to R^2 of 0.78.

Introduction

Acoustic wave propagation in carbonates is known to be highly complex and many aspects remain to be explained. In pure carbonates measured under equal pressure and saturation, porosity and pore structure are the dominant parameters that determine acoustic velocities (Anselmetti and Eberli 1993, 1997). Anselmetti and Eberli (1999) demonstrated that deviations in acoustic velocity at any given porosity are controlled by different pore types in carbonates. In particular, they showed how large isolated molds within a cemented, stiff framework cause positive deviations from the Wyllie equation. In contrast, complicated intercrystalline pore types cause generally negative deviations. In addition, decreasing size of moldic pores coincided with a decrease in velocity. Saleh and Castagna (2004) incorporated this knowledge into a model combining Wyllie's equation and Brie's Spherical Porosity Model. They concluded that shape size and distribution of high-aspect-ratio pores stiffens the rock and leads to higher compressional velocities.

In this paper we incorporate quantitatively derived size and tortuosity estimates derived from thin section analysis to enhance the ability to understand the reasons for velocity

deviations from Wyllie's time average equation. In particular we wanted to test how much velocity is influenced by roundness compared to other geometrical pore shape parameters.

Data set and Method

123 carbonate samples were selected to cover a wide range of porosities and pore-types, as well as a variety of ages and geographic locations to produce a widely representative. Porosity values vary from 5% to over 40%, with velocities ranging from 3000 m/s to over 6500 m/s. For all samples quantitative pore shape parameters were calculated using the image analysis tool "Erika" we developed in order to derive more standardized quantitative image parameters using batch calculations.

Quantification of pore structures by digital image analysis of thin sections has been established as a tool to determine size, shape and distribution of grains, cements and porosity (Furley 1995, Lindqvist and Akeson 2001, Erlich et al 1984). We combine commercial database software, public domain image processing package ImageJ using MatLab scripts that allow us to streamline and standardize the image analysis workflow. Image parameters are calculated in batch processing and can be combined easily with other physical parameters.

Thin section preparation, image acquisition, image segmentation and quantification of feature characteristics are the four basic steps in our image analysis workflow. After image acquisition, images are segmented into pore space and rock space using digital photomicrographs from either plain polarized light, or a combination of plain and cross polarized light. The image classification scheme used is performed in the Hue-Saturation-Value colorspace to enhance the accuracy of the procedure.

After the images are binarized, a variety of shape parameters are calculated. Unique and quantitative description of the shapes of two-dimensional objects has been and will continue to be a challenge. The complex internal structure of carbonate rocks poses a specific challenge because no single parameter is capable of capturing unequivocally the essence of a particular object. A combination of shape parameters is usually required to distinguish objects with overall similar characteristics from each other. Russ (1999) describes a variety of such parameters in his Image Processing Handbook. In addition, most computer software programs usable for the purpose of image analysis allow for the calculation of a wide range of such parameters.

Quantification of Velocity-Deviation in Carbonates

In order to compare petrophysical properties to the pore structure of the plug, not individual pores but the pore system as a whole needs to be characterized. Thus, parameters are required that describe quantitatively the characteristics of the arrangement, distribution and shape of individual objects (pores) within the entire thin section. Standard statistics (mean, median, standard deviation etc.) describe the distribution of the individual pore shape parameters. Combinations of parameters and distribution statistics describe the overall characteristics of the sum of all shapes in a given set. Multivariate linear regression is used to determine relationships between geometrical and physical parameters. In addition, they quantify the impact of each geometrical parameter to porosity or velocity prediction.

Results

Figure 1 gives a plot of the velocity-porosity at 20 Mpa of the samples on which elastic, hydraulic, and geometric properties were measured. The data show the characteristic trend in carbonates of increasing velocity with decreasing porosity and the large spread of velocity at any given porosity. For each of these samples a variety of geometrical parameters were calculated and the following three were used for a comparison with the petrophysical data. Figure 2 shows the values of three parameters superimposed in color on a velocity-porosity cross-plot.

The first parameter is Total Perimeter over Area, which is the ratio between the total pore space area on a thin-section and the total perimeter that encloses the pore space. It can

be regarded as a two-dimensional equivalent to tortuosity that is defined as the ratio between pore volume and specific surface. The variation of PoA in Figure 2a ranges from less than $40 \mu\text{m}^{-1}$ to over $250 \mu\text{m}^{-1}$. Low values of PoA distinguish samples with relatively high velocities for their given porosity from samples with relatively low velocities for their given porosity.

Quantification of Velocity-Deviation in Carbonates

The second parameter is Dominant Pore Size (DOMSize), which is determined as the upper bound of pore sizes that contain more than 50% of the porosity on a thin section. Dominant pore sizes range from less than $100 \mu\text{m}^2$ to over $1200 \mu\text{m}^2$ (Figure 2b). Low values of dominant pore size generally are found in samples with relatively low velocities at a given porosity and vice versa. This trend is opposite to the trend observed on the PoA plot (Figure 2).

The third parameter is roundness (γ), which was defined by Anselmetti et al. (1998) as the perimeter over area of individual pore normalized to a circle; i.e. a perfect round circle would have a gamma of one. In our data set, γ varies from 1.5 to 4.5. Low values of γ are generally found in samples with relatively low velocities at a given porosity and vice versa (Figure 2c). This trend is similar as for the Domsize but is less well expressed (Figure 2).

These trends indicate the existence of a 3-dimensional relationship between velocity, porosity and the geometrical properties derived from image analysis. Figure 3 illustrates these relationships in 3-D space. Roundness, PoA, and Dominant pore size are plotted together with a plane representing the best first linear regression surface. Roundness, in contrast to PoA and DOMsize, does not produce a good linear fit (Figure 3).

To assess which subset of geometrical parameters best captures the variations in elastic and hydraulic properties directly we used multivariate linear regression. The general purpose of a multivariate linear regression is to understand the relationship between several predictor variables and a dependent criterion variable. For example, compressional velocity of a rock sample may be dependent on a variety of predictor variables such as porosity, mineralogy, pore type, pore size, shear velocity etc. Once the values of these variables are known for a set of samples, a multivariate linear regression can assess whether and how much these variables contribute to the measured compressional velocity. Mineralogy, porosity, and shear velocity alone do not explain the variability in compressional velocity sufficiently. Additional factors like size and type of pores contribute in variation in compressional velocity. Table 1 shows the results of 5 different multivariate linear regressions with different sets of variables used for prediction of velocity. Velocity prediction from porosity information alone results in large misfits between predicted and observed compressional velocities. An R^2 value of 0.49 clearly indicates a lack of predictive ability if no additional information is available (Table 1). Geometrical pore-shape parameters in combination with porosity increase the accuracy with which velocity can be derived from porosity. The inclusion of γ into the model will enhance prediction to R^2 of 0.52. On the other hand, PoA increases the correlation to R^2 of 0.52. Velocity prediction using a combination of porosity, γ , DOMsize, and PoA can explain almost 80% of the variation leading to R^2 values of 0.786.

The plots to aid Figure 4 show the results of two separate multivariate linear regressions. If sonic velocity is estimated using porosity and roundness as estimators, a R^2 of 0.53 demonstrates that the addition of the roundness parameter does not significantly improve the prediction of sonic velocity. However, if sonic velocity is estimated using porosity and PoA as estimators result in a R^2 of 0.76, demonstrating the value of the additional information contained in this geometrical pore shape parameter.

Figure 3: Relationships between sonic velocity, porosity, Roundness, PoA, and Dominant pore size in 3-D space plotted together with the best first linear regression surfaces.

Quantification of Velocity-Deviation in Carbonates

Estimators used for Prediction	R ²
Porosity (ϕ)	0.490
Porosity & Roundness (γ)	0.524
Porosity & DOMsize	0.684
Porosity & PoA	0.762
ϕ , γ , DOMsize & PoA	0.786

Table 1: Correlation coefficients from five multivariate linear regressions using different input variables as estimators of sonic velocity. A combination of three parameters with porosity significantly improves the correlation.

Conclusion

Digital image analysis can be used to characterize the pore system in carbonates and help to quantify the influence of pore types on velocity. In particular, pore size and tortuosity defined by digital image analysis strongly influence acoustic velocity. The roundness of pores alone has a minor influence and does not significantly enhance the ability to estimate sonic velocity from porosity in carbonate rocks. The combination of three pore shape parameters with porosity is capable of estimating the velocity with a R^2 of 0.78.

References

- Anselmetti, F. S. and Eberli, G.P., 1993, Controls on sonic velocity in carbonate rocks. In: R.C. Liebermann (ed.) *PAGEOH, Pure and Applied Geophysics*, v. 141, No: 2/3, p. 287-323.
- Anselmetti, F. S. and Eberli, G.P., 1997, Sonic velocity in carbonate sediments and rocks. In: Marfurt, F.J. and Palaz, A. (eds.) *Carbonate Seismology: SEG Geophysical Developments Series 6*, p. 53-74.
- Anselmetti, F. S. and Eberli, G.P., 2001, Sonic velocity in carbonates - a combined product of depositional lithology and diagenetic alterations. In: Ginsburg R.N. (ed.), *Subsurface Geology of a Prograding Carbonate Platform Margin, Great Bahama Bank: Results of the Bahamas Drilling Project*. SEPM Special Publication v. 70, p. 193-216.
- Anselmetti, F. S., and Eberli, G.P., 1999, The velocity-deviation log: a tool to predict pore type and permeability trends in carbonate drill holes from sonic and porosity or density logs. *AAPG Bulletin*, v. 83/3, p. 450-466.
- Anselmetti, F.S., Luthi, S., and Eberli, G.P., 1998, Quantitative characterization of carbonate porosity by digital image analysis; *AAPG Bulletin*, v. 82, p. 1815-1836.
- Ehrlich, R., Kennedy, S.K., Crabtree, S.J., and Cannon, R.L., 1984, Petrographic image analysis, I. Analysis of reservoir pore complexes: *Journal of Sedimentary Petrology*, v. 54, p. 1365-1378.
- Fortey, N.J., 1995, Image analysis in mineralogy and petrology. *Mineralogical Magazine*, 59, 177-178.
- Lindqvist, J.E., and Akeasson, U., 2001, Image analysis applied to engineering geology, a literature review. *Bulletin*

of Engineering Geology and the Environment, v. 60, p. 117-122.

Russ, J., 1999, *The Image Processing Handbook*, 3rd Edition, CRC Press, Boca Raton, FL, 771 pp.

Saleh, A.A. and Castagna, J.P., 2004, Revisiting the Wyllie time average equation in the case of near-spherical pores, *Geophysics*, vol. 69, no. 1 pp. 45-55.

Acknowledgments

We appreciate the advice and suggestions offered by Industrial Associates of the Comparative Sedimentology Laboratory. We thank Shell E&P for partial support of this project.

Figure 4: Results of two separate multivariate linear regressions. Top: Sonic velocity is estimates using porosity and roundness as estimators and a R^2 of 0.53 demonstrates the lack of predictability. Bottom: Sonic velocity is estimates using porosity and Perimeter over Area as estimators and a R^2 of 0.76 demonstrates the value of the additional information contained in this geometrical pore shape parameter.