Investigation of the Relationship between Seismic Velocity Dispersion Principles and the Permeability of Subsurface Porous Materials

Adrienne Campbell*, Winnie Pun, Bernd Milkereit; University of Toronto, Toronto, Ontario
campbell@geology.utoronto.ca

GeoConvention 2012:Vision

Summary

A promising relationship exists between frequency dependent velocity dispersion and the seismic attenuation of compressional waves through porous media, and the permeability of subsurface porous materials. The aim of this study is to correlate the relationship between frequency dependent P wave velocity dispersion and the permeability of subsurface porous materials. This is carried out using geophysical data obtained from the Mallik Gas Hydrate Production Research Well Program in the MacKenzie Delta of the Canadian Arctic. This study will elaborate on a case study mapping the relative variation of Mallik MRI-derived permeability values using P wave velocity dispersion logs. If a correlation between subsurface permeability of porous media and frequency dependent velocity dispersion can be equated, this research has the potential to make ground breaking advances in exploration, mining and environmental remediation.

Introduction

The relationship between compressional wave (P wave) velocity as a function of frequency – a term known as velocity dispersion – and the permeability of subsurface porous media has long been the subject of investigation. With this parameter linkage there is potential to make ground breaking advances in exploration, mining and environmental remediation. An enhanced understanding of subsurface fluid flow could provide valuable insight into the structure of a formation and how much groundwater or hydrocarbon product can be produced, the transport of groundwater contamination, a more thorough understanding of flow characteristics in oil and gas reservoirs, better management of water in-take issues and flooding in mines, and could result in reduced exploration costs.

Many widely used methods are available to determine the porosity of subsurface materials, including the sonic log, density log, neutron log, and the nuclear magnetic resonance log. The permeability of subsurface materials, however, cannot be directly determined using conventional borehole log methods. Current methods to measure the permeability parameter, k, include pumping tests, core sample analysis and magnetic resonance imaging (MRI). Such methods are useful, although there are shortcomings to each method. It may be possible, however, to develop a more direct method of measuring permeability.

In porous media, frequency dependent velocity dispersion (ΔV_P) and seismic attenuation (Q^{-1}) exist. If such seismic wave principles could be linked to permeability, it would bring forward an alternative, more direct method of studying fluid flow in porous media without irreversibly damaging the natural geological conditions. Case histories indicate that it is possible to map relative permeability variation using P wave velocity dispersion logs derived from full waveform sonic data (Pun et al). Seismic attenuation has been found to be an impractical parameter to measure, and so this study will expand on the investigation of the relationship between P wave velocity dispersion, and subsurface permeability over a wider range of frequencies and depths.

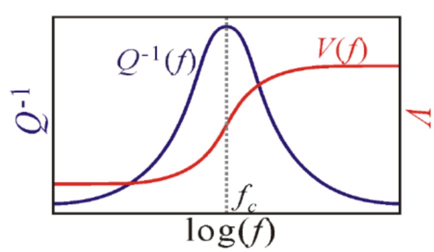


Figure1: P wave velocity and seismic attenuation as a function of frequency (Liu et al, 1976, modified from Pun et al)

Theory and/or Method

The relationship discussed in this paper has been the subject of investigation for numerous groups since the mid-1900`s. Biot developed a theory in 1956 considering the parameter linkage between P wave velocity dispersion and attenuation as a function of frequency in fluid-filled porous medium. In 2005 Pride stated that in a plot of P wave velocity dispersion and seismic attenuation as a function of frequency, the peak seismic attenuation value occurs in conjunction with the greatest velocity dispersion. It is as the seismic attenuation approaches this point that Pride believes that the slope is inversely proportional to permeability. This relationship can be seen in Figure 1.

A study conducted by Baron and Holliger in 2010, investigating the same parameter linkages, found that seismic attenuation values were habitually too high to be explained by Biot's theory, and that the plot predicted by Pride (Figure 1) did not show the predicted seismic attenuation peak. Seismic attenuation is not a practical parameter to obtain, as attenuation encompasses many factors in addition to the effect of the permeability of the subsurface material. Thus, it is more practical to examine the effect of subsurface permeability on P wave velocity dispersion.

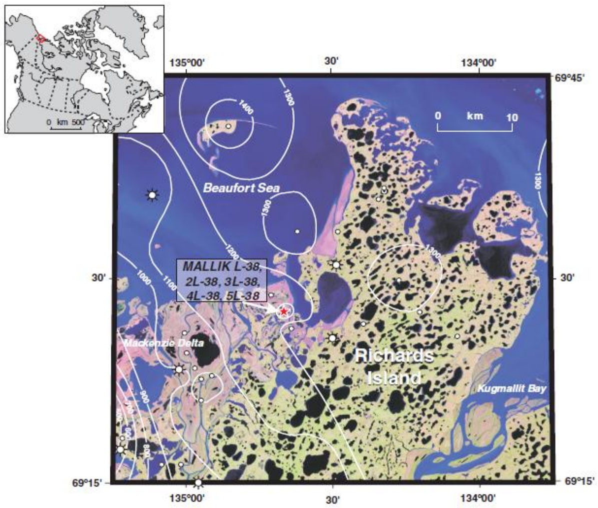


Figure 2: Location map of the 2002 Mallik Gas Hydrate Production Research Well Program (Geological Survey of Canada Bulletin 585 (2005))

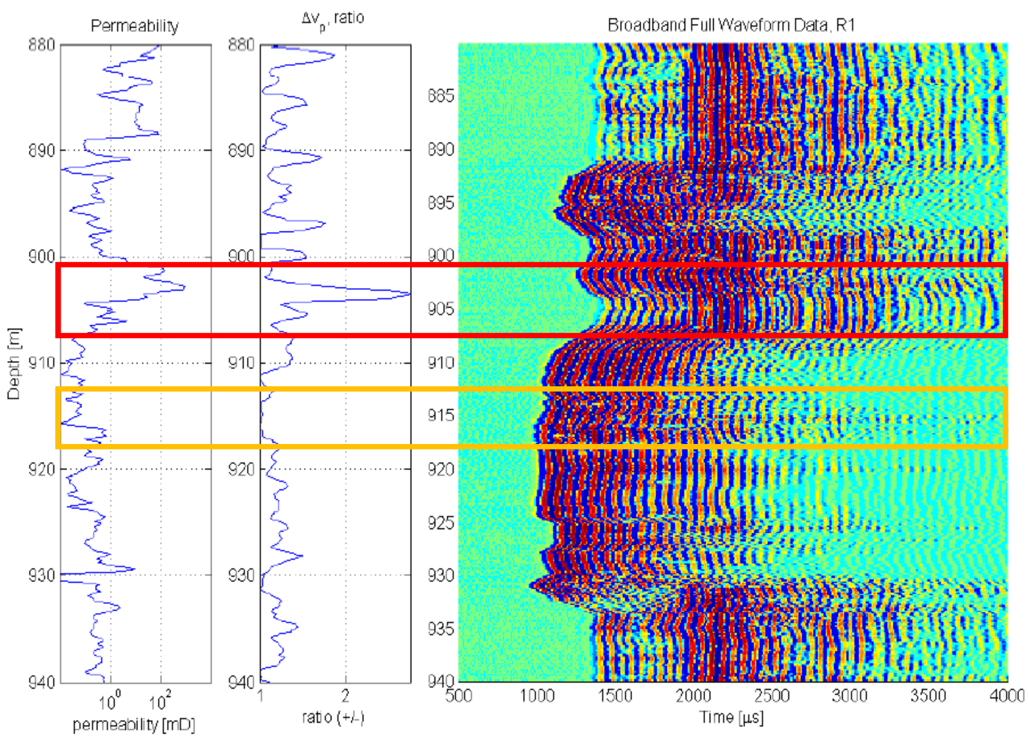


Figure 3: MRI-derived permeability values, P-wave velocity dispersion ratio values (computed using the cross correlation method outlined in Pun et al) and broadband full waveform data recorded by receiver 1 in the Mallik 5L-38 research well. The areas of high and low velocity dispersion ratios are outlined in red and yellow respectively. (Based on Pun et al)

Geophysical data from the 2002 Mallik Gas Hydrate Production Research Well Program is available in this study. The aim is to correlate the MRI-derived permeability with theoretically derived permeability estimates based on velocity dispersion data. A location map of the Mallik site can be seen in Figure 2.

Figure 3 displays the MRI-derived permeability values, the P-wave velocity dispersion ratio values (computed using the cross correlation method outlined in Pun et al) and the broadband full waveform data recorded by receiver 1 in the Mallik 5L-38 research well. The broadband signal contains frequencies ranging from 1 to 30 kHz. In Figure 3, an area of high P wave velocity dispersion ratio – corresponding to high permeability values, slow P wave arrival times and low gas hydrate saturations – is outlined in red. An area of low P wave velocity dispersion ratio – corresponding to low permeability values, fast P wave arrival times and high gas hydrate saturations – is outlined in yellow.

Further correlation of physical parameters as a function of depth is found in the borehole logs shown in Figures 4 and 5. Figures 4 and 5 display the NMR-density log derived gas hydrate saturations, P wave velocity and CMR Permeability computed using the SDR model for the Mallik 5L-38 well. High and low permeability zones of the borehole log in Figures 4 and 5 are outlined in green. The trends exhibited in Figures 5 and 6 correlate with those seen in Figure 3. High permeability zones exhibit low P wave velocities and low gas hydrate saturations. Low permeability zones exhibit high P wave velocities and high gas hydrate saturations.

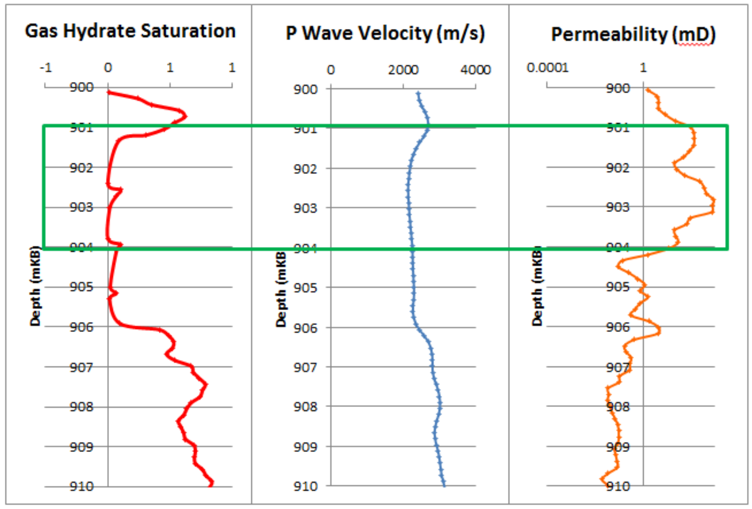


Figure 4: NRM-density log derived gas hydrate saturation, P wave velocity and CMR permeability computed using SDR model borehole logs for a high permeability zone of the Mallik 5L-38 well.

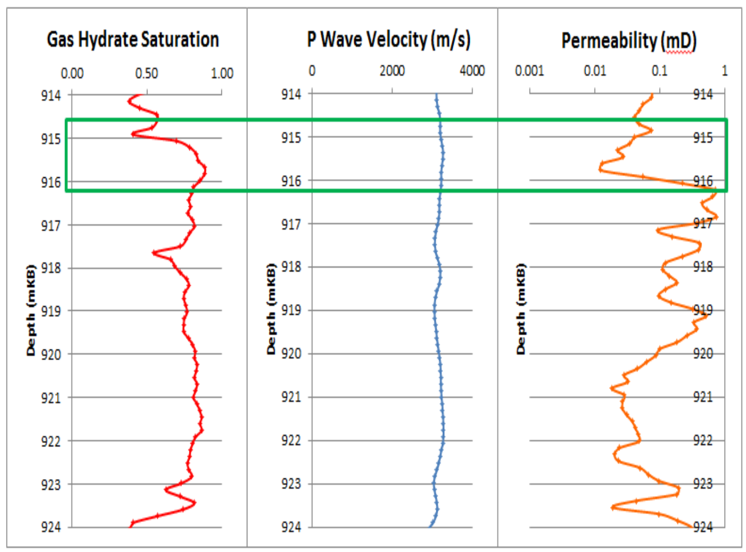


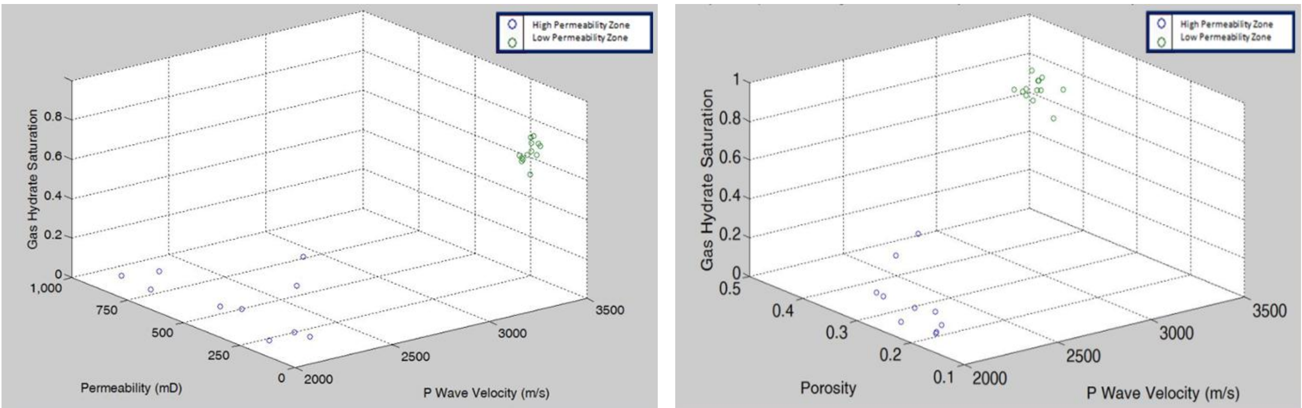
Figure 5: NRM-density log derived gas hydrate saturation, P wave velocity and CMR permeability computed using SDR model borehole logs for a low permeability zone of the Mallik 5L-38 well.

A three dimensional representation of the physical properties in the high and low permeability zones of the Mallik 5L-38 well, represented by blue and green data points respectively, is seen in Figure 6. High permeability zones are found in more porous zones, with lower gas hydrate saturation and lower P wave velocities. Low permeability zones are found in less porous zones, with higher gas hydrate saturations and higher P wave velocities.

The trends seen in Figures 3 to 6 are consistent; there are grounds to believe that a correlation exists. Data analysis is to be carried out over a wider frequency range and over larger depth intervals in order to equate a relationship between permeability and velocity dispersion.

Examples/Implications

It is of interest to utilize this study in the practical application of fluid flow in porous media. In the Canadian Arctic, evidence of vertical fluid flow can be seen in the form of pingos or mud volcanoes. In the case of gas hydrates, it is important to investigate the flow of dissociated methane hydrate components not only in the vertical direction, but also in the horizontal direction. If horizontal fluid flow is present, it could speed up the dissociation of the gas. A better understanding of this phenomenon will aid with the knowledge of how the gas can be produced. The evolution of the gas hydrate reservoir model can be seen in Figure 7. If the final stage of the model is accurate, both vertical and horizontal fluid flow is possible.



Figures 6a and 6b: 3D visualization of the correlation between gas hydrate NMR-derived gas hydrate saturation, P wave velocity and CMR Permeability computed using SDR model (Figure 6a) and density log-derived porosity (Figure 6b) for the high and low permeable zones of the Mallik 5L-38 well, shown in blue and green respectively.

Conclusions

Using the cross correlation method described in Pun et al, P wave velocity dispersion is observed in the geophysical data obtained from the Mallik Gas Hydrate Production Well Program.

The P wave velocity dispersion has great potential to be correlated with subsurface permeability. If this promising link can be validated, there is potential to make ground breaking advances in exploration, mining and environmental remediation.

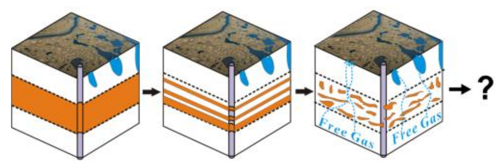


Figure 7: Evolution of the gas hydrate reservoir model (based on Huang et al, 2009)

Acknowledgements

This research is funded by the Natural Sciences and Engineering Research Council (NSERC).

References

Baron, L. and Holliger, K., 2010. Poro-elastic Analysis of the Velocity Dispersion and Attenuation Behaviour of Multifrequency Sonic Logs: Advances in Near-surface Seismology and Ground-penetrating Radar.

Biot, M.A. (1956). Theory of propagation of elastic waves in a fluid-saturated porous solid: The Journal of Acoustical Society of America, 28,168-178.

Geological Survey of Canada Bulletin 585 (2005). Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Program, MacKenzie Delta, Northwest Territories, Canada. Eds. Dallimore, S.R. and Collett, T.S..

Huang, J.-W., G. Bellefleur, and B. Milkereit, 2009. Seismic Modeling of Multidimensional Heterogeneity Scales of Mallik Gas Hydrate Reservoirs, Northwest Territories of Canada: Journal of Geophysical Research, 114.

Liu, H.-P., D. L.Anderson, and H. Kanamori, 1976, Velocity dispersion due to anelasticity; implications for seismology and mantle composition: Geophysical Journal of the Royal Astronomical Society, 47, 41–58.

Pride, S. R. (2005). Hydrogeophysics, 9, 253-290. Springer.

Pun, W., B. Milkereit, and B. Harris. (2010). Extraction of Permeability Variations from P-Wave Velocity Dispersion Data: Near Surface 2010