Journal of Applied Sciences

ISSN 1812-5654

science alert

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 14 (11): 1180-1185, 2014
ISSN 1812-5654 / DOI: 10.3923/jas.2014.1180.1185

Rock Physics Modeling and Fluid Substitution Studies in Sandstone Reservoir

I.A. Purnamasari, H. Khairy, A.L. Abdeldayem and W. Ismail
Faculty of Geoscience and Petroleum Engineering, Universiti Teknologi PETRONAS,
Seri Iskandar, Tronoh, 31750, Perak Darul Ridzuan, Malaysia

Abstract: The link between various geological parameters and rock physics properties, including cement volume, clay volume and degree of sorting, can be used to perform lithology substitution from observed rock types assumed to be present nearby. Rock physics models can be used to provide the link between trends in velocity and porosity as well as velocity and clay content in reservoir rocks. Three models were established for water-saturated rock to gas saturated which are the friable-sand model, the contact cement model and the constant cement model and Gassmann theory as a tool for predicting pore fluid from the elastic properties of water-saturated sandstone reservoir. They were used to analyzed P-wave velocity versus porosity trends. P- and S-wave velocity for the constant cement model shows more closely to the measured P- and S-wave velocity log.

Key words: Rock physics properties, rock physics models, reservoir rocks, constant cement model

INTRODUCTION

Rock physics knowledge is required to analyse the elastic properties (P- and S-wavevelocity, density, impedance and ratio of P- and S-wave velocity) which acts as a bridge that links the elastic properties to the reservoir properties such as water saturation, porosity and shale volume (Avseth, 2000). The reservoir parameters such as lithofacies, porosity, pore fluid type, saturation and pore pressure can be very well understood with the help of rock physics. All of those parameters are directly or indirectly sensible tothe seismic velocity of the subsurface formation. Thus, rock physics can be applied to predict reservoir parameters, such as lithologies and pore fluids derived from seismic attributes, especially in undrilled areas and thereby reducing risks of exploration.

Key aspects for geophysicists when modeling seismic reflectivity and interpreting seismic data is to predict elastic properties of reservoir rock and their dependance on porosity and pore fluid. In this context, the fluid substitution method is an important tool, because it makes it possible to predict the elastic response of a rock saturated with one type of fluid from the elastic response of the same rock saturated with another fluid (Gommesen *et al*., 2002).

There are several important theories in rock physics, of which Gassmann's model probably is the most well-known. It used to predict how P- and S-wave velocity are changed as saturation changes. Since the Gassmann model is based on some specific assumptions, the index of rocks and fluid properties with these assumptions should be evaluated before its application. In addition to Gassmann's method, there are some other theories which can be used in the estimation of the bulk and shear modulus and at last P- and S-wave velocity. Effective medium theory and elastic contact theory are some of the models which can be used in rock physics. In this study, Gassmann's theory will be applied in well log data and the rock physics models. Results of these models will be reviewed and compared to well log data. Rock properties analysis and log response of clean sand area were discussed in this study. The Boonsville field was chosen for this study because the dataset is publicly available from the Bureau of Economic Geology (BEG) at the University of Texas in Austin. The dataset was generated as part of The Secondary Gas Recovery (SGR) project supported by Gas Research Institute and the U.S Department of Energy.

The objective of this study is to compare how well the predicted response of fluid substitution methods using Gassmann's equation applied to rock physics models, match log data from Boonsville Field. Three contact models were established, by fluid substitution compare the predictions with the elastic behavior of clean sand and well grain contact assumption and also by fluid substitution of elastic behavior of well log data detected as gas.

Corresponding Author: I.A. Purnamasari, Faculty of Geoscience and Petroleum Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, Tronoh, 31750, Perak Darul Ridzuan, Malaysia Tel: 60134449964

MATERIALS AND METHODS

Rock physics models

Gassmann's theory (Gassmann, 1951): The most widely-used theory for fluid substitution is the low frequency Gassmann's theory. Gassmann's equation gives a relationship between saturated bulk modulus, porosity, bulk modulus of minerals of minerals of rock matrix and the bulk modulus of pore fluids (Mavko *et al.*, 1998):

$$K_{sat} = K_{dry} + \frac{\left(1-\frac{K_{dry}}{K_m}\right)^2}{\frac{\phi}{K_{fl}} + \frac{(1-\phi)}{K_m} + \frac{K_{dry}}{K_m^2}} \tag{1}$$

where, K_{sat} is the saturated bulk modulus, K_{dry} is the bulk modulus of dry rock frame, K_m is the bulk modulus of the rock matrix, k_{fl} is the bulk modulus of pore fluids and k_m^2 is the porosity. Gassmann's equation is based on several assumptions which must be taken into account in any application (Wang, 2001): (1) Rock (matrix and frame) must be macroscopically homogeonous; (2) All pores must be interconnected; (3) Pores are filled with a frictionless fluid; (4) The rock-fluid system must be closed (undrained); (5) There should be no interaction between fluid and the matrix in a way that could make the frame soften or harden. The first assumption implies that the wavelength must be greater than the pore and grain sizes. The second assumption indicates that the porosity and permeability must be high and there should be no isolated or poorly connected pores. Second and third assumptions explain why the well log and laboratory velocity data often are higher compared to Gassmann's predictions. In general, relative fluid-matrix movements are more prominent for some special frequencies and might create large differences between bulk and shear modulus of fluid and matrix. With these assumptions and Eq. 1, saturated bulk modulus, K_{sat}, can be estimated. By knowing K_{sat}, P- and S-wave velocity can be predicted by Eq. 2 and 3 (Mavko *et al.*, 1998):

$$V_p = \sqrt{\frac{K_{sat} + \mu}{\rho b}} \tag{2}$$

$$V_S = \sqrt{\frac{\mu}{\rho b}} \tag{3}$$

where, μ and ρ_B are the shear modulus and bulk density, respectively.

Friable-sand model or HMHS model (Dvorkin and Nur, 1995): This model for unconsolidated sediments assumes porosity reduction from the initial sand pack value (critical porosity) due to the deposition of solid matter away from the grain contacts that result in gradual stiffening of the rock. This porosity reduction for clean sandstone is caused by depositional sorting and packing. The elastic modulus at the critical porosity end point ($\sqrt{c}$) are given by Hertz-Mindlin (HM) theory. The zero porosity point represents the mineral point. These two points are connected by the unconsolidated line represented mathematically by the modified lower Hashin-Shtrikman (MLHS) bound. The saturated elastic modulus can be calculated using Gassmann's Eq. 1, then also V_P and V_S can be obtain using Eq. 2 and 3.

Contact-cement model (Dvorkin and Nur, 1995): During burial of sandstones, cementation by diagenetic quartz, calcite other minerals results in a strong stiffening because welding of the grain contacts. The contact cement model describes the porosity reduction from initial sand pack due to uniform deposition of cement layers on the surface of grains that result in a sharp increase in velocity with decreasing porosity.

Constant-cement model (Avseth, 2000): This model is a combination of the friable-sand model and the contact cement model. It assumes that the sands of varying porosity all have the same amount of contact cement and variation within this group is due to non contact pore filling (e.g., sorting). Porosity initially decreases from critical limit, $\sqrt{c}$ to $\sqrt{b}$ (cemented porosity) solely due to cementation. From $\sqrt{b}$ porosity decreases as in the case of friable sand model. Since the amount of cement is of ten related to depth, this model is also called 'the constant cement depth model'. In the other hand, sorting is related to lateral variation in flow energy during sediment deposition (Avseth, 2000).

Geology of study area: The method is applied in the seismic datasets of Bend Conglomerate reservoir system in Boonsville field, located in the Fort Worth Basin of North-Central Texas. The Secondary Gas Recovery (SGR) Boonsville study area is located in Jack and Wise Counties in the Fort Worth Basin in North-Central Texas (Fig. 1a). The field is one of the largest natural gas fields in the U.S. It produces gas with some oil which comes from conglomeratic sandstones deposited during the Atoka Group of the Middle Pennsylvanian Period. A generalized post-Mississippian description of the stratigraphy of the Fort Worth Basin is shown by the

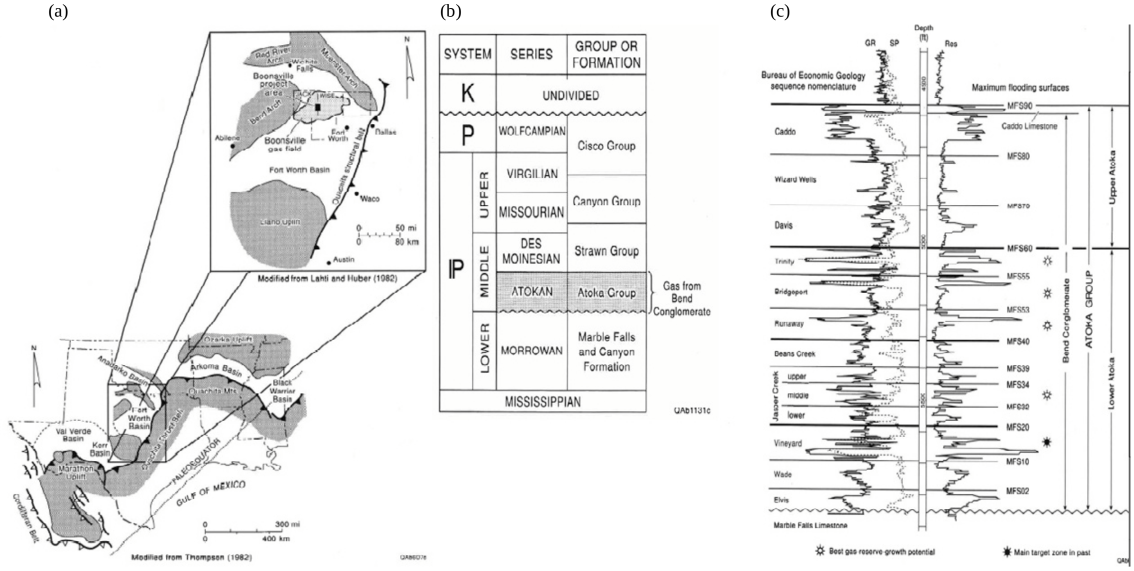

Fig. 1(a-c): (a) Middle Pennsylvanian paleogeographic map showing the Fort Worth Basin and other basins related to the Ouachita orogeny and the Boonsville project area. (b) Generalized post-Mississipian stratigraphic column for the Fort Worth Basin. (c) Stratigraphic nomenclature used to define Bend Conglomerate Genetic sequences in Boonsville Field

stratigraphic column in Fig. 1b. The Bend Conglomerate of Atoka Group is defined as the interval from the base of the Caddo Limestone to the top of the Marble Falls Limestone (Fig. 1c). Within the SGR study area, the thickness of the Bend Conglomerate ranges from 1000 to 1200 ft (305-365 m). The target in this field is Runaway level. This level was chosen for this study because it is suspected as gas producing level and as best gas-reserve-growth potential. The depth of Runaway level ranges from 5299 to 5372 ft sub-sea and the clean sand zone of this level ranges from 5315 to 5331 ft.

RESULTS AND DISCUSSION

Log data from vertical well from Boonsville field is selected for this study. The gamma ray log shows the well contains of shale and sands (Fig. 2). Three models were established from water saturated rock into gas saturated. The elastic modulus of the dry-well sorted end member at critical porosity are modeled as an elastic sphere pack subject to confining pressure, given by the Hertz-Mindlin theory (Mindlin, 1949).

In rock physics modeling need to define the end members between which other members are interpolated. The mineral point which is at zero porosity is the low porosity end member while the high porosity member would depend on the lithology being investigated. Due to the inherent porosity of clay minerals in shales, shales are usually deposited with a higher initial porosity (critical porosity) than sands. This critical porosity defines the high porosity end-member at a given pressure. The elastic stiffness at this porosity is estimated by using the contact theory or some other alternative theory such as Hertz-Mindlin theory. Since the region of interest in Runaway Layer is a clean sand area, in this study, the critical porosity was defined 40% for clean sandstones.

Most sands rich in quartz have bulk modulus of the mineral matrix ranging from 35-40 GPa and shear modulus of the mineral matrix from 35-44 GPa (Smith, 2011). In this study, a solid bulk modulus and shear modulus for quartz are assumed 36.6 and 45 GPa, respectively and for clay are 17.5 and 7.5 GPa, respectively. Mixed modulus for both minerals are computed by Voigt-Reuss average. The elastic constants and other parameters used in this study show in Table 1.

Comparing well log data with contact theories using gassmann's theory: By measuring P- and S-wave velocity and knowing rock and fluid properties, saturated bulk modulus can be estimated using Gassmann's Eq. 1. Based

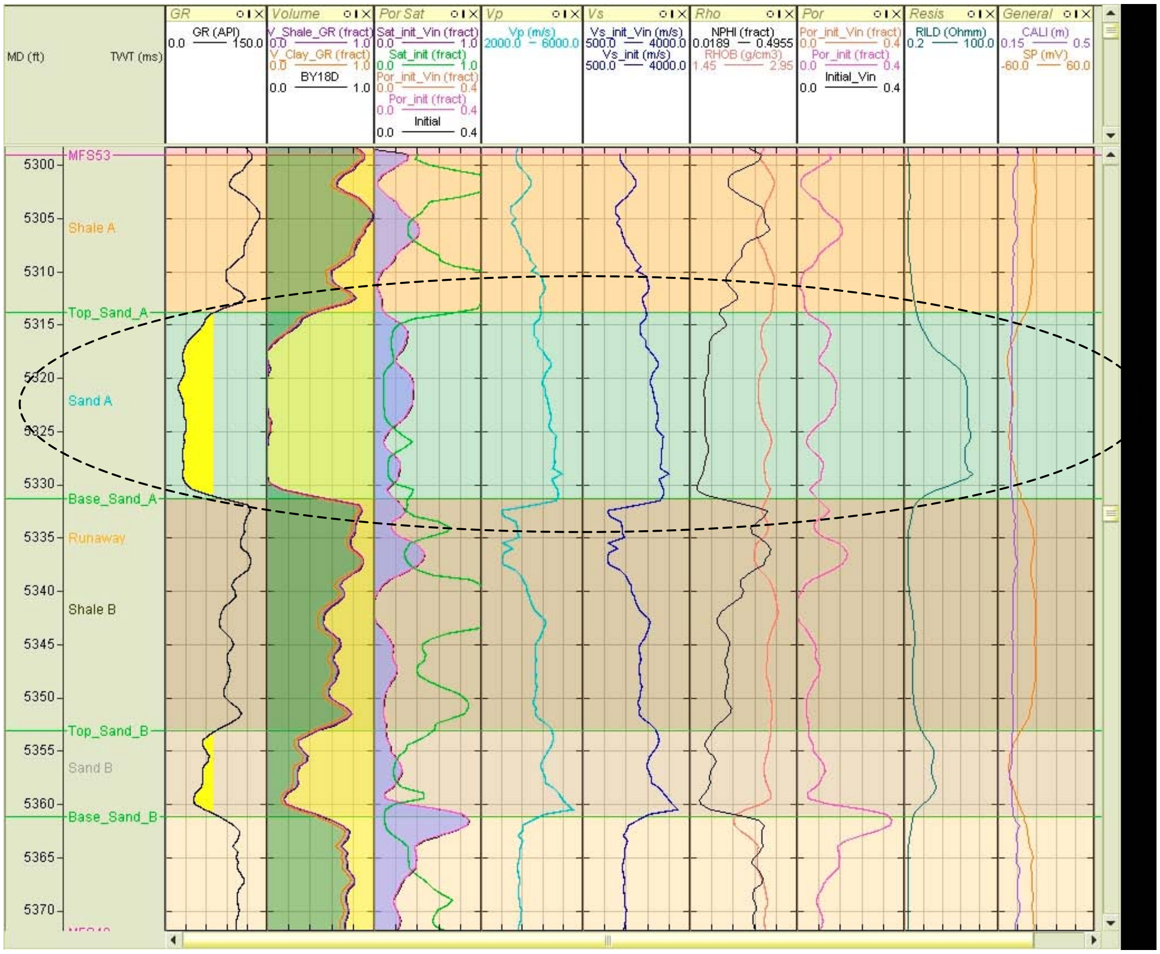

Fig. 2: Log responses of gamma ray, velocities, density, neutron, resistivity, porosity, water saturation within the depth interval that embodies reservoir in Runaway Layer. Dashed line indicates the clean sand area (region of interest)

Table 1: Mineral properties are averaged from Mavko *et al*. (1998)

Parameter	Value (GPa)	Parameter	Value
Bulk modulus of clay (Kclay)	17.5	Bulk modulus of gas (Kgas) (GPa)	7.5
Shear modulus of clay (μclay)	7.5	Density of quartz (kg m^{-3})	2650
Bulk modulus of quartz (Kqtz)	36.6	Density of clay (kg m^{-3})	2300
Shear modulus of quartz (μqtz)	45.0	Density of water (kg m^{-3})	1000
Bulk modulus of water (Kwtr)	2.2	Density of gas (kg m^{-3})	150

on Gassmann's assumptions, shear modulus is supposed to be equal to the dry case. Now, using Eq. 2, P-wave velocity can be calculated for the saturated case. Since the area of interest is a clean sand zone, S-wave velocity was predicted by Vs empirical method prediction for sandstone line. The result showed that the provided shear log was good. The main input logs were the P-wave velocity (Vp), S-wave velocity (Vs) and the density (Rho) logs. The main working intervals focused within the reservoir sandstones.

In Fig. 2, the density depth trend for Sand A shows an almost steady increase in density with depth. This could be the effect of cementation at higher depth which increases both density and rock stiffness. The effect of cementation would however, be more on the rock frame than the density.

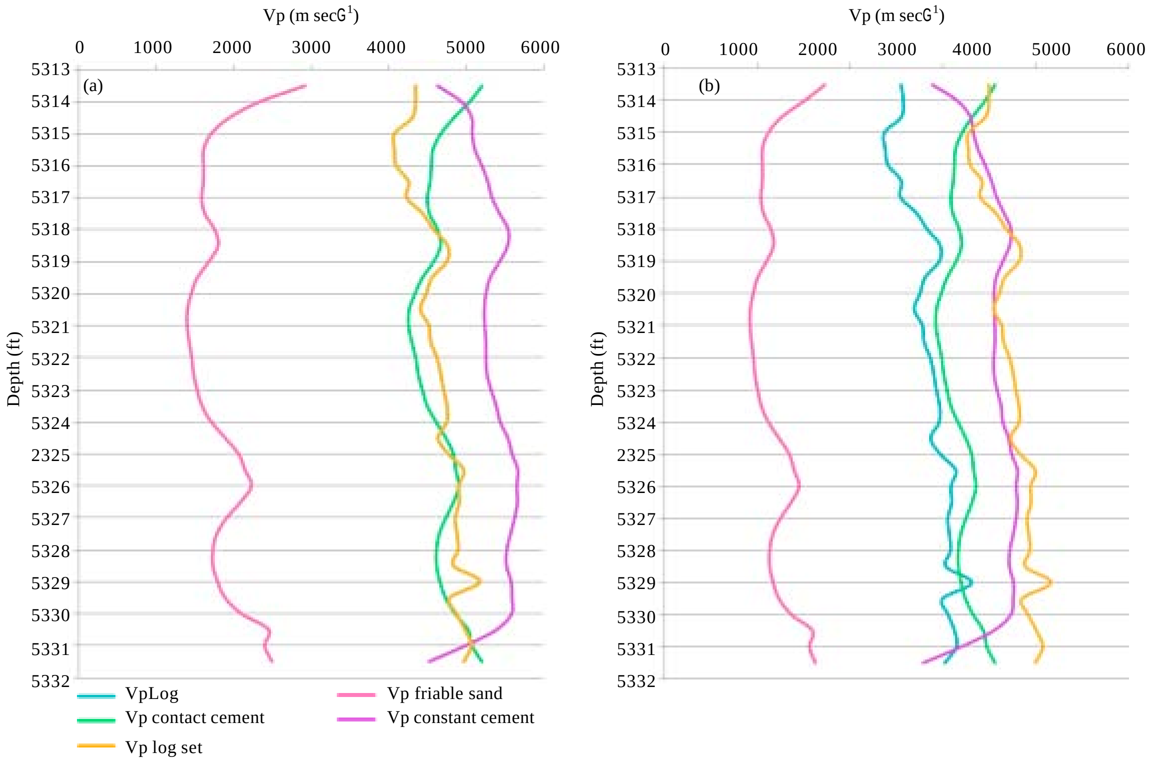

Fig. 3(a-b): Depth versus velocities. (a) P-wave velocity and (b) S-wave velocity

Figure 3 shows that the Gassmann theory provides a better prediction of S-wave velocity of the log. The constant cement model in saturated gas condition is the best fit correspond to velocity log.

CONCLUSION

In this study, the application of Gassmann theory and contact theories has been tested. Fluid substitution from water saturated to gas saturated was performed and compared to the accoustic log response. From the results can be concluded:

- The well-log data in this study has good information content
- The rock physics study show that rock physics models are useful in diagnosing fluid and lithology interpretation

The constant cement model is the best fit applied for P-wave velocity prediction matched with log response.

ACKNOWLEDGMENT

Authors would like to thank the Bureau of Economic Geology for providing access to their 3-D seismic and production data.

REFERENCES

Avseth, P., 2000. Combining rock physics and sedimentology for seismic reservoir characterization of North Sea turbidite systems. Ph.D. Thesis, Stanford University, USA.

Dvorkin, J.P. and A.M. Nur, 1995. Elasticity of high-porosity sandstones: Theory of two North sea datasets. Proceedings of the SEG Annual Meeting, October 8-13, 1995, Houston, Texas, pp: 890-893.

Gassmann, F., 1951. Elastic waves through a packing of spheres. Geophysics, 16: 673-685.

Gommesen, L., G. Mavko, T. Mukerji and I.L. Fabricius, 2002. Fluid substitution studies for North Sea chalk logging data. Proceedings of the SEG Annual Meeting, October 6-11, 2002, Salt Lake City, Utah.

Mavko, G., T. Mukerji and J. Dvorkin, 1998. The Rock Physics Hand Book: Tools for Seismic Analysis in a Porous Media. Cambridge University Press, Cambridge, UK.

Mindlin, R.D., 1949. Compliance of elastic bodies in contact. J. Applied Mech., 16: 259-268.

Smith, T.M., 2011. Practical seismic petrophysics: The effective use of log data for seismic analysis. Leading Edge, 30: 1128-1141.

Wang, Z., 2001. Fundamentals of seismic rock physics. Geophysics, 66: 398-412.