Jurnal Natural
Vol. 23, (3) 2023
DOI 10.24815/jn.v23i3.30980
pISSN 1411-8513
eISSN 2541-4062
ORIGINAL RESEARCH

Relationship between seismic acoustic impedance (AI) and total organic carbon (TOC) content: a case study from Australia

MUHAMMAD RIDHA ADHARI[1*], MUHAMMAD YUSUF KARDAWI[2]

[1]Department of Geological Engineering, Faculty of Engineering, Universitas Syiah Kuala
[2]Faculty of Computer Science, Universitas Indonesia

Abstract. Shale gas has become of interest of geoscientists globally because of its potentials to expand our energy supply. This research used well logs data and total organic carbon (TOC) data from Perth and Canning Basins, Australia. The objective of this research is to investigate source rock potential of the study area by examining the relationship between TOC content and seismic acoustic impedance (AI) derived from well log data, using regression analysis. The outcomes of this research show that for claystone/siltstone, the relationship between AI and TOC is nonlinear, while for shale the correlation is linear. However, there is no fixed equation that can be used as a standard for this linear/nonlinear relationship. Results show that for a certain type of lithology, the relationship between TOC and AI is different for different formations. This is interpreted to be caused by different depositional environment, diagenesis, mineralogical composition and different depth of burial. Findings of this study are expected to provide some new insights into the relationship between AI and TOC for various types of lithology and contribute to shale gas exploration studies.

Keywords: Shale gas, Acoustic impedance, Total organic carbon, Canning Basin, Perth Basin

INTRODUCTION

Shale gas has succesfully provided an additional source of energy needed for our daily life, and recently has transformed a net importer of natural gas country like USA into a net producer and exporter [1,2,3,4]. Perth and Canning Basins (both located in Western Australia) are known to be prospective, with many commercial oil and gas fields in operation [5,6,7,8,9,10]. Many oil and gas companies including Buru Energy, Australian Worldwide Exploration (AWE), Norwest Energy and Westralian Gas and Power (WGP), and academic research groups were involved in shale gas exploration and development in Canning and Perth Basins [11,12,13]. It is estimated that the Canning Basin has recoverable shale resources of 222 trillion cubic feet (TCF), while the Perth Basin has about 59 TCF [14]. Shale gas research should be encouraged to optimize these prospective resources and hopefully this research will have a significant impact in exploration and production of shale gas.

*Corresponding Author:
mr.adhari@usk.ac.id

Received: February 2023 | Revised: June 2023 | Accepted: July 2023

Rock-Eval Pyrolysis is usually used to identify the type, maturity, and characteristics of total organic carbon content (TOC) [15,16]. However, this method is expensive and can only be used in areas with abundant rock samples. Acoustic impedance (AI), a product of sonic velocity (Vp) and density (ρ), (AI = Vp x ρ), can provide a solution to overcome the limitation of the rock-eval pyrolysis. AI is relatively easier to be acquired, and cheaper to be analysed. A better understanding of the relationship between AI and TOC may provide a solution that can be used to estimate TOC using the data from AI, or vice versa. Thus, it would help in lowering the exploration cost/analytical cost (no need to conduct rock-eval pyrolysis) and could save a certain amount of money for the companies.

The main objective of this study is to investigate source rock potential of the Perth and Canning Basins by examining the relationship between AI and TOC content. The outcomes would be useful in predicting organic richness of shale from seismic data, or vice versa. It is expected that by combining the analysis of AI and TOC, a better understanding of the characteristics of shale gas can be achieved. The result of this research can help us improving our

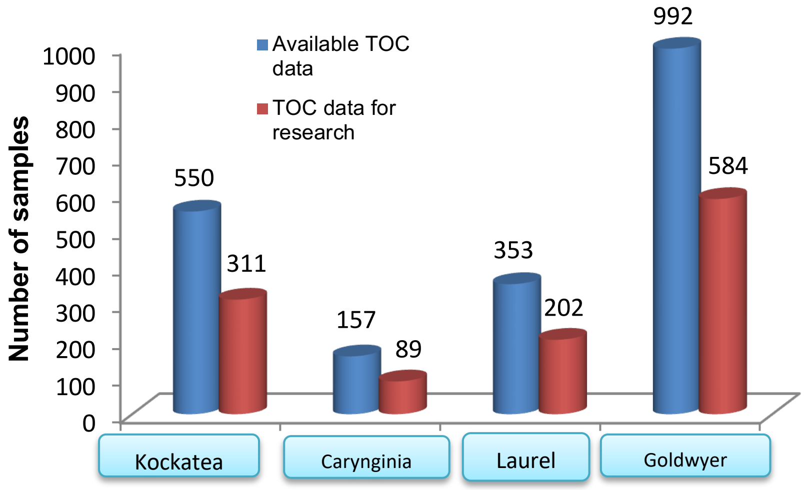

Figure 1. Comparison of TOC data from four formations. Kockatea and Carynginia formations are located in the Perth Basin, while Laurel and Goldwayer formations are located in Canning Basin.

understanding of shale characteristics, which is very important for shale gas system evaluation.

DATA AND METHOD

This study used TOC, AI, and wireline log data from the Perth Basin (Kockatea shale, and Carynginia Formations), and Canning Basin (Laurel, and Goldwyer Formations), Western Australia. These data were analysed using regression analysis method to achieve the objective of this study.

A total of 2,052 TOC data are available, however only 1,186 data are suitable to be analysed to achieve the objective of this study (Figure 1). Acoustic impedance is a product of seismic velocity and density and is normally represented by the equation 1 [17]. Acoustic impedance is a basic physical rock property and it can yield important information concerning the nature of the rock and changes in lithology. AI is a rock parameter affected by the type of lithology, porosity, fluids contents, depth, pressure and temperature [18]. Therefore, AI can be used as an indicator of lithology, porosity, hydrocarbon, lithology mapping, flow unit mapping, and reservoir character quantification [18]. The AI will be controlled mostly by the wave velocity [18].

$$Z = Vp \; x \; \rho \qquad (1)$$

Where Z = Acoustic impedance (m/s x g/cm^3)
Vp = Sonic velocity (m/s)
ρ = Density (g/cc)

Two types of wireline log data were used for this research and these are sonic velocity log (Vp), and density log (RhoB). Most of the studied wells have the DT data, which is the slowness of sonic velocity log (Vp). This DT data need to be converted to sonic velocity log and equation 2-3 was used for this conversion. Microsoft Office Excel was used for this conversion and it was done cautiously especially when dealing with the unit of DT (μs/ft) and Vp (m/s). Density log is required for acoustic impedance conversion, however, not all of the studied wells have this data. Density estimation using Gardner equation [19] was conducted to tackle this problem. Gardner equation or Gardner relation (equation 4) is an empirical derived equation that relates Vp (sonic velocity) to the density (RhoB).

$$Vp = \frac{1}{DT} \qquad (2)$$

$$Vp = \frac{1}{DT} x \; 0.3048 \; x \; 1000000 \qquad (3)$$

Where Vp: Sonic velocity log (m/s)
DT: Slowness (μs/ft)

$$\rho = A \; x \; Vp \; x \; B \qquad (4)$$

Where ρ = Density (g/cc)
A = 0.31, if Vp is in m/s
A = 0.23, if Vp is in ft/s
B = 0.25 (constant)

Regression analysis is one of the most widely used techniques for analysing multi-factor data, and is defined as a statistical technique for investigating and modelling the relationship between variables [20]. In almost all applications of regression, the regression equation is only an approximation to the true functional relationship between the variable of interest. An important objective of regression

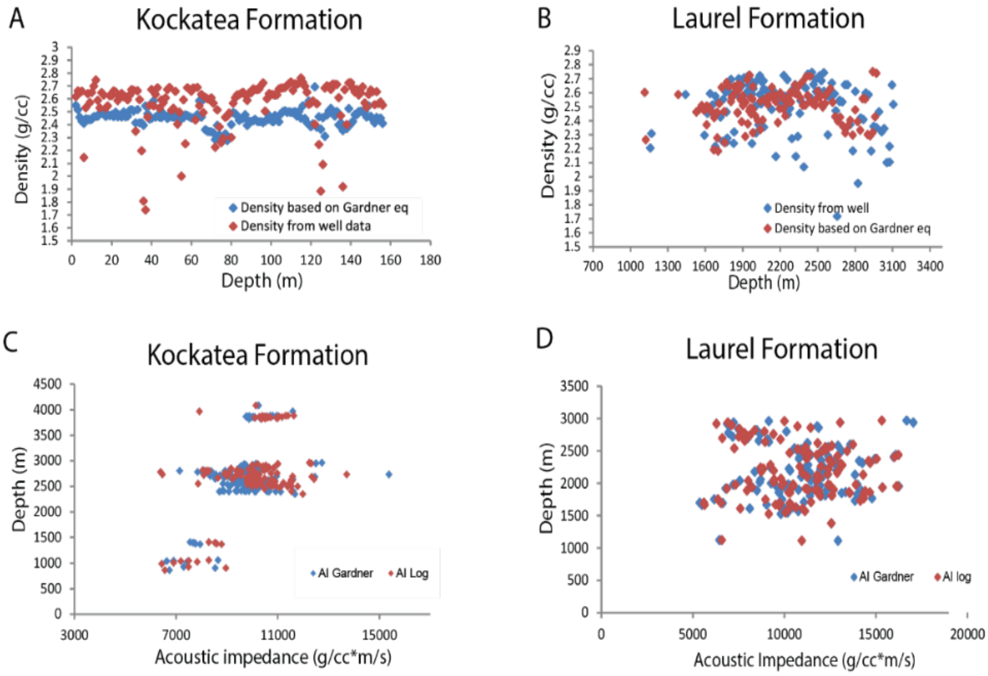

Figure 2. A. Comparison between density from log data and density from Gardner equation using the data from Kockatea Formation, Perth Basin. B. Comparison between density from log data and density from Gardner equation using the data from Laurel Formation, Canning Basin. C. Comparison between AI from log data and AI from Gardner equation using the data from Kockatea Formation. D. Comparison between AI from log data and AI from Gardner equation using the data from Laurel Formation.

analysis is to estimate the unknown parameters in the regression model. This process is also called fitting the model to the data.

Regression analysis was developed to detect the presence of a mathematical relation between two or more variables subject to random variation, and to test if such a relation, whether assumed or calculated, is statistically significant [21]. If one of these variables stands in causal relation to another, that variable is called the independent variable. The variable that is affected is called the dependent variable. There are two types of regression analysis: linear regression analysis and nonlinear regression analysis. In linear regression, data is modelled using linear predictor functions, and unknown model parameters are estimated from the data. Such models are called linear models. nonlinear regression is a form of regression analysis in which observational data are modelled by a function which is a nonlinear combination of the model parameters and depends on one or more independent variables. The data are fitted by a method of successive approximations.

RESULTS AND DISCUSSION

Density and acoustic impedance values

Some well data used in this study contain a complete set of density log, while many wells do not have this type of data. An estimation of density log was done to overcome this issue. These estimation results are considered acceptable and reliable, and a comparison of the estimated density versus the recorded density log is shown in Figure 2.A-2.B. Moreover, two types of acoustic impedance were generated: (1) AI using estimated density, and (2) AI using recorded density. Comparison between these two different AI is provided in Figure 2.C-2D.

Kockatea Formation

A total of 311 samples data have been analysed for Kockatea Formation, Perth Basin. 122 samples from 20 wells are grouped as Shale (red colour), 60 samples from 14 wells are categorized as claystone/siltstone (blue colour) and 123 samples from 24 wells are classified as sandstone (green colour). It can be clearly seen that there are three different trends associated with three different dominant lithologies (Figure 3).

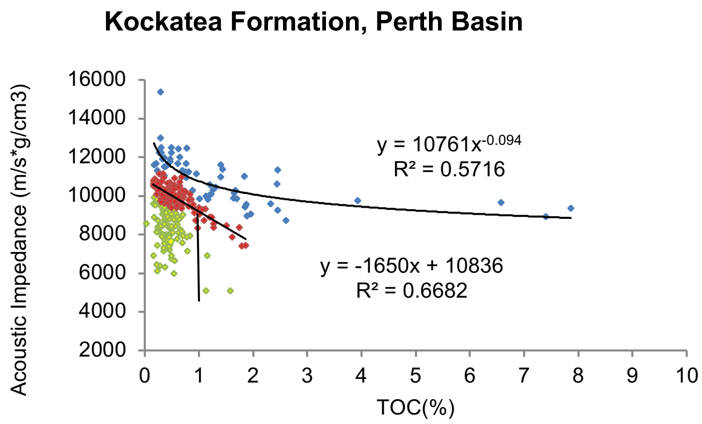

Figure 3. Sample data from Kockatea Formation, Perth Basin. Green points = sandstone, red points = shale, blue points = claystone/siltstone. R^2 = Coefficient of determination, measures how well a statistical model predicts an outcome.

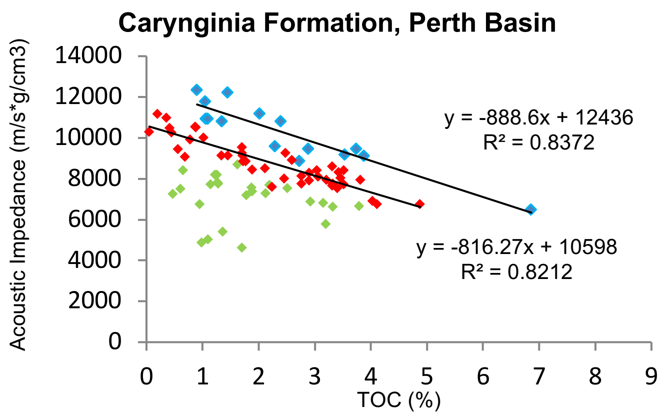

Figure 4. Sample data from Caryngina Formation, Perth Basin. Green points = sandstone, red points = shale, blue points = claystone/siltstone. R^2 = Coefficient of determination, measures how well a statistical model predicts an outcome.

Results (Figure 3) show that for the Kockatea Formation, the relationship between AI and TOC for claystone/siltstone is expressed by a power equation:

Y = 10761X-0.094 (5)

Where

Y = Acoustic impedance (m/s x g/cm^3)
X = TOC (%)

The AI value of claystone/siltstone decreases when the TOC percentage increases. This change follows the power equation, which is a nonlinear equation. TOC content ranges from 0.17–7.86 (%) and the value of AI ranges between 8717–15367 (m/s x g/cm^3) and the average is 10934 (m/s x g/cm^3) (Figure 3).
While for shale, the relationship between acoustic impedance and TOC is linear and is expressed by equation:

Y = -1650X + 10836 (6)

Where

Y = Acoustic impedance (m/s x g/cm3)
X = TOC (%)

The acoustic impedance ranges between 7391–11130 (m/s x g/cm^3) and the minimum TOC is 0.15% and the maximum value is 1.86% (Figure 3). Shale has relatively lower acoustic impedance than claystone/ siltstone. There is no certain relationship between acoustic impedance and TOC for sandstone and from the Figure 3, it's clear that as the AI value increases there is no significant changes in TOC content. This means that the changes of AI will not affect the TOC and vice versa.

Caryngina Formation

The relationship between AI and TOC for the data from the Caryngina Formation, Canning Basin, is shown in Figure 4, with three different colours represent three different dominant

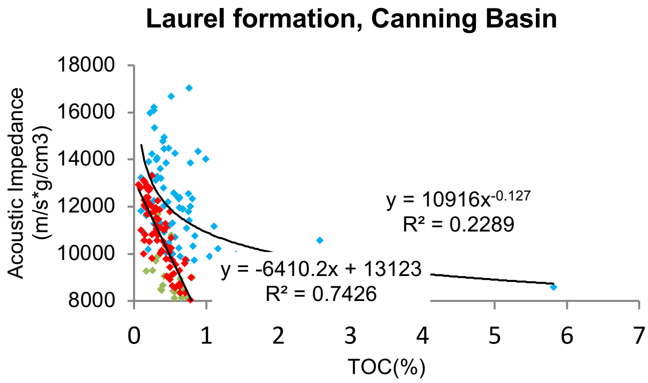

Figure 5. Sample data from Laurel Formation, Canning Basin. Green points = sandstone, red points = shale, blue points = siltstone. R^2 = Coefficient of determination, measures how well a statistical model predicts an outcome.

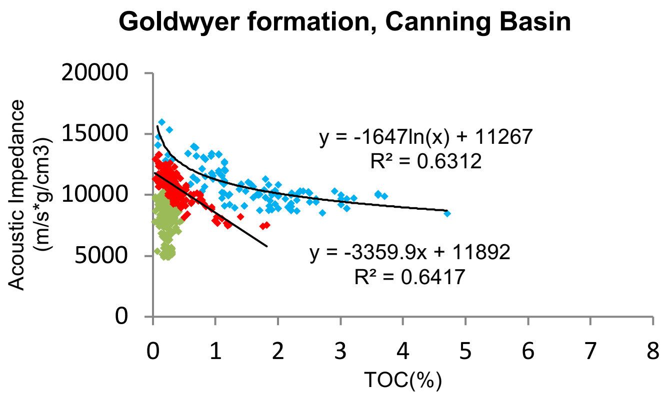

Figure 6. Sample data in Goldwyer Formation, Canning Basin. Blue points = claystone, red points = shale, and green points = limestone. R^2 = Coefficient of determination, measures how well a statistical model predicts an outcome.

lithologies. Results show that the claystone/siltstone (blue colour) has the acoustic impedance value from 8890–12356 (m/s x g/cm^3) and the TOC value ranging between 0.9%–3.88% (Figure 4). The relationship between AI and TOC for claystone/siltstone is expressed by a linear equation, which is:

$$Y = -888.6X + 12436 \quad (7)$$

Where

Y = Acoustic impedance (m/s x g/cm3)

X = TOC (%)

Moreover, the relationship between AI and TOC for shale (red points in Figure 4) is expressed by a linear equation, which is:

$$Y = -816.27X + 10598 \quad (8)$$

Where $R^2 = 0.8212$

Y = Acoustic impedance (m/s x g/cm^3)

X = TOC (%)

Even though shale and claystone/siltstone have the same linear relationship, these lithologies can be distinguished by its AI value. For shale, the AI value is ranging between 6766–1119 (m/s x g/cm^3) and claystone/siltstone has relatively higher AI value (Figure 4). With the same TOC percentage, claystone/siltstone will have higher AI value than shale.

AI value for sandstone is ranging between 4624 – 8723 (m/s x g/cm^3) and the TOC is between 0.47% - 3.79% (Figure 4). It's difficult to find the relationship between AI and TOC for sandstone. There is no linear/non-linear equation, that best represent this relationship with an acceptable correlation coefficient.

Laurel Formation

The relationship between AI and TOC for the Laurel Formation is shown in Figure 5. Results of this study show that the relationship between AI and TOC for siltstone in the Laurel Formation can be expressed by a power equation, which is:

$$Y = 10916X\text{-}0.127 \quad (9)$$

Where

Table 1. Equations that represent Claystone/siltstone in each formation.

Formation	Basin	Lithology	Equation	R²
Kockatea	Perth	Claystone/Siltstone	$y = 10761x^{-0.094}$	$R^2 = 0.5927$
Carynginia	Perth	Claystone/Siltstone	$y = -888.6x + 12436$	$R^2 = 0.8372$
Laurel	Canning	Siltstone	$y = 10916x^{-0.127}$	$R^2 = 0.2909$
Goldwyer	Canning	Claystone	$y = -1647\ln(x) + 11267$	$R^2 = 0.6312$

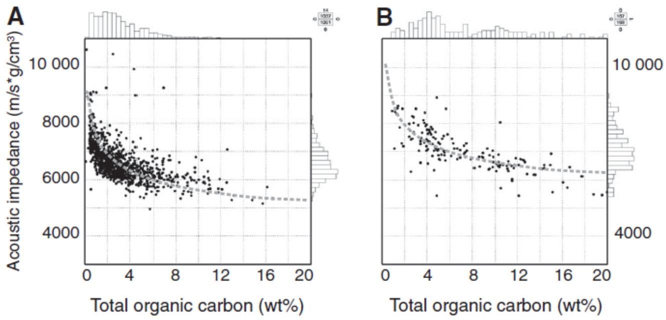

Figure 7. A. TOC versus AI plot for Metherhills Quarry well in Kimmeridge Clay in southern England. B. Similar plot for Hekkingen Formation, Barents Sea, from 9 wells [22].

Y = Acoustic impedance (m/s x g/cm^3)
X = TOC (%)

Moreover, the values of AI ranges between 7426-17038 (m/s x g/cm^3) and the minimum TOC is 0.1% while the maximum TOC percentage is 5.81% (Figure 5).

The acoustic impedance value for shale in this formation is between 6225–13295 (m/s x g/cm^3) and the TOC ranges from 0.06%-1.04% (Figure 5). Shale, which is represented by red colour (Figure 5) has a different trend with siltstone. It can be clearly seen that as AI decreases, the TOC increases (Figure 5). The relationship between AI and TOC for shale in the Laurel Formation is shown by a linear equation, which is:

$$Y = -6410.2X + 13123 \quad (10)$$

Where
Y = Acoustic impedance (m/s x g/cm^3)
X = TOC (%)

The correlation between acoustic impedance and TOC for sandstone in this formation is still not known, and there is no representative equation. Some sandstone data show that as AI decreases, the TOC increases. However, other data show that as AI increases the TOC also increases (Figure 5).

Goldwyer Formation

Goldwyer formation can be divided into three main lithologies: (1) claystone which is represented by blue points; (2) shale which is shown by red points; and (3) limestone which is marked with the yellow points (Figure 6). Each of these lithologies has different data trend (Figure 6). The value of AI ranges between 8502–16005 (m/s x g/cm^3) and the minimum TOC is 0.07% while the maximum is 4.7% (Figure 6). Findings from this study show that the relationship between AI and TOC for claystone in Goldwyer Formation is expressed by a logarithmic equation:

$$Y = -1647\ln(X) + 11267 \quad (11)$$

Where Y = Acoustic impedance (m/s x g/cm^3)
X = TOC (%)

For shale, the relationship between TOC and AI is shown by a linear equation, which is:

$$Y = -3359.9X + 11892 \quad (12)$$

Where $R^2 = 0.6417$

Y = Acoustic impedance (m/s x g/cm^3)
X = TOC (%)

Shale has a relatively lower AI value than claystone and for the Goldwyer Formation the value of AI is ranging between 7465 – 1332 (m/s x g/cm^3) and the TOC of shale is between 0.03% - 1.82% (Figure 6).

The relationship between AI and TOC for limestone is still not known, and there is no representative equation for this lithology. As can be seen in the Figure 6, when the AI value of limestone increases, the TOC is stable without any changes. This means that for limestone, the changes in AI will not affect

Table 2. Minimum and maximum value of depth, AI and TOC for claystone/siltstone

Formation	Depth (m)		AI (g/cm^3 x m/s)		TOC (%)	
	min	max	min	max	min	max
Kockatea	1054.5	4082	8717.368	15367.18	0.17	7.86
Caryngina	1499	3787	8890.73	12356.93	0.9	3.88
Laurel	1113	4326	7426.004	17038.21	0.1	5.81
Goldwyer	1190.5	2801.2	8502.738	16005.58	0.07	4.7

Table 3. Equation that represents shale in each formation.

Formation	Basin	Lithology	Equation	R^2
Kockatea	Perth	Shale	y = -1650x + 10836	R^2 = 0.6682
Caryngina	Perth	Shale	y = -816.27x + 10598	R^2 = 0.8212
Laurel	Canning	Shale	y = -6410.2x + 13123	R^2 = 0.7426
Goldwyer	Canning	Shale	y = -3359.9x + 11892	R^2 = 0.6417

Table 4. Minimum and maximum value of depth, AI and TOC for Shale

Formation	Depth (m)		AI (g/cm^3 x m/s)		TOC (%)	
	min	max	min	max	min	max
Kockatea	290	3966	7391.46	11130.94	0.15	1.86
Caryngina	275.2	3659	6766.53	11191.49	0.05	4.88
Laurel	1122.6	3124.5	6225.099	13295.09	0.06	1.04
Goldwyer	910	3900.8	7465.935	13326.71	0.03	1.82

TOC and vice versa. Limestone has a relatively low AI which is between 4941 –10797 (m/s x g/cm^3) (Figure 6).

The lithology from Figure 3-6 can be grouped into 3 categories: claystone/siltstone, shale and sandstone/limestone. It can be clearly seen that for shale and claystone/siltstone as the acoustic impedance value decreases the TOC percentage increases. The relationship between AI and TOC for those lithologies is different as shale consistently has linear relationship (Figure 3-6), while for claystone/siltstone the correlation between AI and TOC is expressed by power equation (Figure 3 and 5), linear equation (Figure 4) and exponential equation (Figure 6).

There is no linear or non-linear equation that can best represent the relationship between AI and TOC for sandstone/limestone. Figure 3 and 6 show that for sandstone/limestone as the AI increases, the TOC is stable, without any changes. Figure 4 and 5 some data show that as the AI decreases the TOC increases while other data show that as AI decreases, the TOC also decreases. Sandstone and limestone are not the focus of this study since they can't be a source rock or produce any gas shale.

The outcome of this study (relationship between AI and TOC) for claystone/siltstone is similar with the studies conducted by [22]. Based on their studies of cores and well logs, AI, which is the product of compressional velocity and density, decreases nonlinearly with increasing TOC percent (Figure 7). However, [22] did not show the type of nonlinear equation that is best in representing this relationship.

Table 1 shows the equations that represent claystone/siltstone in each studied formation. R^2 value, which is the coefficient of determination, is more than 0.5 in 3 formations (Kockatea, Caryngina, and Goldwyer), and only in Laurel Formation it is lower than 0.5. This means that the relationship between AI and TOC for Laurel formation is less reliable. Excluding Laurel Formation, there are three other formations left that can be used to identify the relationship between AI and TOC for claystone/siltstone. Even though the Caryngina Formation has a very good R^2 value (0.84), the sample data used for this lithology is very limited (14 samples from 6 wells and only one data with TOC more than 4%). Therefore, on this basis, the equation generated for the Caryngina formation is also considered less reliable. This means that the relationship between AI and TOC for claystone/siltstone can only be identified from Kockatea and Goldwyer Formations.

Kockatea and Goldwyer formations have R^2 value higher than 0.5 and the samples data that were analysed for this formation is more than 50 samples. The correlation between TOC and AI for claystone/siltstone in Kockatea Formation is expressed by a power equation and for Goldwyer it is shown by a logarithmic equation. Although the equation that represents this relationship is different, both formations have a nonlinear relationship between AI and TOC. This nonlinear relationship for claystone is similar with the studies by [22]. Therefore, it can be concluded that the relationship between TOC and AI for claystone/siltstone is nonlinear, however there is no standard nonlinear equation that can be used to represent this relationship.

The minimum value of acoustic impedance for Kockatea, Caryngrinia, Laurel and Goldwyer Formations is ranging between 7426–8890 (g/cm^3 x m/s) for claystone/siltstone. While the maximum acoustic impedance value for this lithology within the aforementioned formations is different for each formation (Table 2).

Based on the results from 4 different formations (Kockatea, Caryngrinia, Laurel, Goldwyer) from the Perth and the Canning Basins, the relationship between AI and TOC for shale is best expressed by a linear equation (table 3). However, in each formation this linear relationship is represented by different linear equation (table 3). The R^2 value for all the equations for shale is more than 0.5 (table 3). This means that all those equations (table 3) are considered reliable and acceptable. Those equations (Table 3) show that the AI value is not zero when the TOC value is zero. This can be proved by changing parameter X with zero, then parameter Y will not be zero (Y is the value of TOC and X is the value of AI). The comparison for AI value and TOC percentage for all the studied formations is shown in Table 4.

The minimum value of AI for shale in Kockatea, Caryngrinia, Laurel, and Goldwyer Formations ranges between 6225–7465 (g/cm^3 x m/s) and the maximum value of AI is between 11130–13326 (g/cm^3 x m/s). Kockatea, Laurel, and Goldwyer Formations have the maximum TOC percentage ranging between 1.04%–1.86% (table 4). On the basis of this TOC data, it is interpreted that the equations provided in table 3 only valid for the sample data with TOC value <2%. These equations are not applicable if the sample data have TOC >2%.

Moreover, Caryngrinia Formation has the maximum TOC value of 4.88 %, with excellent R^2 value of 0.82 (table 3). However, this result for Caryngrinia Formation is based on 43 sample data. It is still unknown how the relationship between AI and TOC for shale in Caryngrinia Formation would be if more data are available.

Different equation that represents different lithology (claystone/siltstone and also shale) in those four formations as has been discussed earlier might be caused by different depositional environment. Based on the report from [23] and [24], and also from various well completion reports, both Kockatea and Caryngrinia Formation were deposited in a shallow marine environment. While Laurel Formation was deposited in a lagoonal to marginal marine/restricted marginal marine environment. Moreover, Goldwyer Formation depositional environment is open marine (low energy, unaerobic environment, quiet water). Shallow marine, open marine and lagoonal environments have different characteristic relating to its sediment sources, diagenesis or transportation mechanism [25,26]. The different depositional environment affects the organic richness of shale and also affects the mineralogical composition of shale [25,27]. This can cause different AI value and different TOC percentage. That is why no standard equation that can be used to identify the relationship between AI and TOC for all studied formations.

In addition, different depth in which those lithologies were buried can also generate different equation for the studied formations. When certain rocks were buried deep beneath the earth, the pressure and temperature will also increase and that resulted in a compact, less porous rock [28]. Even though it has the same lithology, the compaction or the porosity of those lithologies might be different and that can affect the physical properties of AI and TOC.

CONCLUSION

This study tried to find the relationship between acoustic impedance (AI), and total organic carbon (TOC) for shale and claystone/siltstone. Findings of this study show that the relationship between AI and TOC for shale is represented by a linear equation, while for claystone/siltstone it is represented by a non-linear equation. There is no fixed/standard linear/non-linear equation that can be used to represent the relationship between AI and TOC for shale and claystone/siltstone. Each lithology from different formation has its own equation. Different equation that represents different lithology is interpreted to be caused by different depositional environment, diagenetic processes, depth of burial and mineral composition.

ACKNOWLEDGMENT

Authors would like to thank Geological Survey of Western Australia for allowing us to work with their subsurface dataset, and for publication of the results.

REFERENCE

[1] Hefley, W. E.; Wang, Y. 2015 Economics of unconventional shale gas development, case studies and impacts (London: Springer)

[2] Rezaee, R. 2015 Fundamentals of gas shale reservoirs (Canada: Wiley)

[3] Wang, Y.; Hefley, W. E. 2016 The global impact of unconventional shale gas development: economics, policy, and interdependence (Switzerland: Springer)

[4] Ridley, M. 2011 The shale gas shock (London: The global warming policy foundation)

[5] Geoscience Australia. 2020 Regional geology of the northern Perth Basin (Australia: Geoscience Australia)

[6] Seyedmehdi, Z. 2019. Sequence stratigraphy influenced by tectonics and implications for reservoir development, latest Devonian–Early Carboniferous ramp, Canning Basin, Australia. *Mar. Pet. Geol.* **99** 252-264. doi: 10.1016/j.marpetgeo.2018.10.002.

[7] Tupper, N.; Matthews, E.; Cooper, G.; Furniss, A.; Hicks, T.; Hunt, S. 2016. The Waitsia Field, onshore North Perth Basin, Western Australia. *APPEA J.* **2016** 29-43.

[8] Broad, D.S. 1973 Canning basin, geology and hydrocarbon potential of the south canning basin, Western Australia (Australia: West Australian Petroleum Pty, Ltd)

[9] Tupper, N.P. 1992 Source potential of the onshore Perth Basin (Australia: Sagasco resources limited)

[10] Burt, A. 2002 Petroleum prospectivity of the eastern Canning Basin, WA (Australia: Dept of Mineral and Petroleum Resources)

[11] Hinai, A. A.; Rezaee, R.; Esteban, L.; Labani, M. 2014. Comparisons of pore size distribution: A case from the Western Australian gas shale formations. *J. Unconv. Oil Gas Resour.* **8**: 1-13.

[12] Labani, M. M.; Rezaee, R.; Saeedi, A.; Hinai, A. A. 2013. Evaluation of pore size spectrum of gas shale reservoirs using low pressure nitrogen adsorption, gas expansion and mercury porosimetry: A case study from the Perth and Canning Basins, Western Australia. *J. Pet. Sci. Eng.* **112:** 7-16.

[13] Sharifzadeh, A.; Mathew, N. 2011. Shale gas in Western Australia. *Petro. in West. Aus.* **4**.

[14] Petromin. 2012. Australian shale gas breezes, blowing but not a gale yet. *Uncon. Gas Rep.* **3**: 8-16.

[15] Bohacs, K. M.; West, B. P.; Grabowski, G. J. 2011 Predicting Source Occurrence, Character, and Distribution in Frontier Settings using Paleo-Environmental Factors: The Source RER Modeling System (Source Retrodiction & Environmental Reconstruction) (London: Geological society).

[16] Majewska-Bill, M.; Felix, M.; Rinna, J.; Mann, U. 2011 Insights into Organic Carbon Source Fractions and Depositional Environment from Geochemical Bulk Parameters. (London: geological Society)

[17] Becquey, M.; Lavergne, M.; C. Willm. 1979. Acoutic impedance logs computed from seismic traces. *Geophysics* **44**(9): 1485-1501.

[18] Sukmono, S. 2007 Post and Pre Stack Seismic Inversion for Hydrocarbon Reservoir Characterization (Indonesia: ITB Press).

[19] Gardner, G.H.F.; Gardner, L.W.; Gregory, A.R. 1974. Formation velocity and density, the diagnostic basics for stratigraphic traps. *Geophysics*.**39**: 770-780.

[20] Montgomery, D.C.; Peck, E.A.; Vining, G.A. 2012 Introduction to linear regression analysis, 5th edition (New Jersey: John Wiley & Sons).

[21] Oosterbaan, R.J. 1994. Frequency and Regression Analysis. In: H.P.Ritzema (ed.), Drainage Principles and Applications. **16** 175-224, (Netherlands: International Institute for Land Reclamation and Improvement).

[22] Løseth, H.; Wensaas, l.; Gading, M.; Duffaut, K.; Springer, M. 2011. Can hydrocarbon source rocks be identified on seismic data?. *Geology* **39**: 1167-1170.

[23] Cadman, S.J.; Pain, L.; Vuckovic, V.; Podevin, S.R.L. 1993. Canning Basin, W.A (Australia: Bureau of Resource Sciences).

[24] Cadman, S. J.; Pain, L.; Vuckovic, V. 1994. Australian petroleum accumulations report 10, Perth Basin, Western Australia (Australia: GSWA).

[25] Nichols, G. 2009. Sedimentology and stratigraphy, 2nd edition (UK: Wiley Blackwell).

[26] Boggs, S. 2014. Principle of sedimentology and stratigraphy (USA: Pearson).

[27] Prothero, D.R.; F. Schwab. 2014. Sedimentary geology, an introduction to sedimentary rocks and stratigraphy, 3rd edition (New York: W.H. Freeman and Company).

[28] Flugel, E. 2010. Microfacies of carbonate rocks, second edition (London: Springer).