Seismic wave attenuation in carbonate rock and its implication to hydrocarbon-bearing reservoir identification, East Java, Indonesia

A Sadat1, A Haris2, Haryono3, A Riyanto2, and G A Dharmawan3
1Department of Physics, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Depok 16424, Indonesia
2Geophysics Study Program, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Depok 16424, Indonesia
3Saka Indonesia Pangkah Limited, Jl. Jend. Sudirman, Jakarta, 12910, Indonesia
Corresponding author’s email: aharis@sci.ui.ac.id

Abstract. The heterogeneity of carbonate rock properties triggers propagated seismic wave to get some attenuations. This mechanism allows that attenuation can be applied in hydrocarbon exploration to identify lithology, porosity, fluid content and fracture identification. Unfortunately, to measure the degree of attenuation, the sophisticated tools and advanced processing technology are required. Thus, some methods were formulated to estimate attenuation. This study is aimed to estimate and compare attenuation from wireline log interpretation by using four different methods. The study is also supported by a series of exploration wells penetrating Kujung I Formation in northwestern edge of North East Java Basin, Indonesia. The result shows that only Qs from Zhang et al method is overestimate. P-wave quality factor of Klimentos and Zhang methods and scaled quality factor (SQp and SQs) method are sensitive to identify hydrocarbon. Furthermore, lithofacies also affects estimated rock quality factor. The novelty of study is to estimate and compare the attenuation from different method and review its result and application in hydrocarbon identification, especially for carbonate reservoir in North East Java basin, Indonesia. So that, a new understanding of attenuation characteristic in carbonate reservoir contributes to discriminate pore fluid identification in hydrocarbon exploration.

Keywords: Seismic wave attenuation, carbonate reservoir, Kujung Formation, hydrocarbon exploration

1. Introduction

The study of seismic wave attenuation has been developed in many years. On the earlier, study was more focused on the cause of seismic attenuation and the effect of fluid in a medium to attenuation. Recently, the attenuation is widely used both in conventional and in unconventional hydrocarbon exploration [1]. Attenuation is sensitive to lithology, fluid saturation, fluid-filled fracture, and porosity [2]. Unfortunately, to estimate the attenuation, sophisticated tools such as full waveform sonic log and vertical seismic profile is required. Furthermore, it also requires high-end technology processing. These issues lead other seismic attributes more popular than attenuation. As an alternative option,
wireline log can be used to estimate the attenuation by using some equations formulated from the relationship of the attenuation and rock properties [3].

The study area covers Muriah Trough-Bawean Arch, northwest part of North East Java Basin. It is a back-arc basin formed by Paleogene extensional tectonic in Eocene. Since Miocene, Neogene compressional tectonic took place resulting tectonic inversion and reactivation in many faults and shale diapirism [4]. The proven reservoir is Kujung I Formation. It comprises of thick and massive limestone and common reefal build up. It was settled on shallow marine setting in Early Miocene with good to excellent reservoir properties [5]. Unlike in its most region, proven hydrocarbon bearing reservoir in study area is sandstone reservoir of Tawun Formation. Due to reserve issue, exploration to deeper target of reservoir become interesting. Moreover, the gas discovery of Lengo-1 well brings new opportunity to explore Kujung I Formation [6]. Gas content on carbonate reservoir may give some effect that is interesting to study.

This study is aimed to estimate seismic wave attenuation by using wireline log on partially saturated carbonate rock of Kujung I Formation. All equations used on this study were formulated from sandstone sample. So that, the study is also to test all those methods on carbonate rock and to identify the effect of fluid content to seismic wave attenuation.

2. Materials and method

The study is using a series of wireline logs from exploration well in Northwestern part of Northeast Java Basin penetrating into Kujung Formation. Firstly, lithofacies identification is conducted by using gamma ray log either uranium-free corrected gamma ray log (CGR) or total gamma ray log (GR). Then, petrophysic analysis was conducted to determine volume of shale, porosity, and water saturation. Petrophysic analysis was calculated by deterministic approach. Moreover, compressional slowness log, shear slowness log and density log play significant role in calculating elastic rock properties.

Inelastic attenuation, one of attenuation mechanism, occurs when the friction between propagated seismic wave with vibrating particle in a medium happened [7]. Some kinetic energy will be transformed into heat energy and cause attenuation. The degree of attenuation in a medium is affected by the heterogeneity of rock properties such as porosity and water saturation.

Attenuation is measured by rock quality factor, Q. It depicts the magnitude of conserved seismic wave which has travelled along medium. So many methods can be used, but on this research will be focused only on four different methods. First method is proposed by Klimentos et al. [8]. Equation was formulated from core sample that was tested under 40 MPa of pressure and 1 MHz of frequency in laboratory. The result is showing linear relationship between porosity and coefficient attenuation. So that, the equation can be formulated as seen in equation 1:

$$Q_p = \frac{\pi f}{(0.0315 PHIE + 0.241 VSH - 0.132)V_p}$$  \hspace{1cm} (1)

where: $Q_p = $ P-wave quality factor; $PHIE = $ effective porosity; $VSH = $ volume of shale; $f = $ frequency; and $V_p = $ P-wave velocity.

On the second method, the attenuation is stated as the ratio of P-wave quality factor and S-wave quality factor. It was formulated by Mavko et al [9]. This method was adopted from Hudson’s crack theory. It suggests that crack orientation affects the reduction of P-wave modulus on wet saturated medium. Three theorems were proposed from this method. First theorem assumes that the reduction of propagated P-wave is caused by anisotropy effect due to aligned crack orientation. The equation can be seen on equation 2:

$$\frac{Q_p^1}{Q_s^1} = \frac{1 (3\gamma - 2)(\gamma - 2)^2}{4 (\gamma - 1)\gamma}$$  \hspace{1cm} (2)
Second theorem assumes that isotropy effect is introduced by random distributed of crack. The equation can be shown on equation 3:

$$\frac{Q_{P}^{-1}}{Q_{S}^{-1}} = \frac{5}{4} \left( \frac{\gamma - 2}{\gamma - 1} \right) \left[ \frac{2\gamma}{3\gamma - 2} + \frac{\gamma}{3(\gamma - 1)} \right]^{-1}$$

The last theorem assumes that the reduction of S-wave modulus is occurred due to random crack distribution and its isotropy effect. The equation can be seen on equation 4:

$$\frac{Q_{P}^{-1}}{Q_{S}^{-1}} = \frac{1}{\gamma} \left[ \frac{3}{4} + \frac{5}{4} \left( \frac{\gamma - 2}{3} \right) \left( \frac{\gamma - 4}{3} \right)^{2} \right]$$

$$\gamma = \left( \frac{M}{\rho} \right) = \left( \frac{V_{p}}{V_{S}} \right)^{2}$$

where: $Q_{P}$ = P-wave quality factor; $Q_{S}$ = S-wave quality factor; $V_{p}$ = P-wave velocity; and $V_{s}$ = S-wave velocity.

Third method is using equation formulated by Zhang et al [10]. The equation was formulated from statistical method by using the linear relationship of attenuation, rock properties and elastic modulus properties. Attenuation was extracted from vertical seismic profile. It is resulting the coefficient of determination for $Q_{P}$ 0.65 and $Q_{S}$ 0.48. The equation can be seen on equation 6 and equation 7:

$$Q_{P} = 1.95M - 13.63 \frac{V_{P}}{V_{S}} + 37PHIE + 21VSH + 28.6$$

$$Q_{S} = 66.4M - 13.38 \frac{V_{P}}{V_{S}} + 285PHIE + 101VSH - 210$$

where: $Q_{P}$ = P-wave quality factor; $Q_{S}$ = S-wave quality factor; PHIE = effective porosity; $M$ = P-wave modulus (GPa); and VSH = shale volume.

The last method was proposed by Hermana et al [11]. It was adopted from Mavko and Dvorkin’s first theorem [9]. This equation was formulated by expanding fracture density parameter into density porosity and aspect ratio of fracture. Thus, the equation is:

$$SQ_{P}^{-1} = \frac{5}{6} \frac{(\gamma - 2)^{2}}{\rho (\gamma - 1)}$$

$$SQ_{S}^{-1} = \frac{10}{3} \frac{\gamma}{\rho (3\gamma - 2)}$$

where: $SQ_{P}$ = scaled P-wave quality factor; $SQ_{S}$ = scaled S-wave quality factor; $\rho$ = Bulk density; $V_{p}$ = P-wave velocity; and $V_{s}$ = S-wave velocity.
3. Results and discussion

Petrophysical analysis was calculated by using deterministic method. Shale volume was calculated by the averaging of gamma ray log and density-neutron log calculation method. Then, porosity calculation was conducted by using density-neutron log method. Tortuosity factor, cementation exponent and saturation exponent parameters used for water saturation are 1, 1.8, and 2. Formation water salinity was measured from water sample analysis indicating low saline water (20,000–30,000 ppm). After that, water saturation was calculated by using Indonesia equation model due to clay rich reservoir indicating from high neutron log. The result of petrophysical analysis can be seen in figure 1.

Clay-rich reservoir may indicate carbonate reservoir sourced from debris or settled in low energy condition. So that, lithofacies of Kujung I Formation can be distinguished into two types. Those are distinguished based on gamma ray log type and shale content. First lithofacies is high-energy clean carbonate. It is characterized by low and blocky gamma ray log, massif, and thick reservoir with low shale content (< 10 %). Whilst the second facies is low-energy carbonate. It is characterized by serrated type gamma ray log, thin reservoir with higher shale content (> 10 %). It is sometimes found interbedding layered with shale.

The next step is calculating the dynamic elastic rock properties to find p-wave modulus (M), s-wave modulus (G), and VpVs ratio. It was calculated by using a series of slowness log and density log such as compressional slowness log (DT), shear slowness log (DTS) and density log (RHOB).

Attenuation was estimated by using four different method. The whole result can be seen in figure 1. By using Klimentos and McCann method, there is separation of high energy carbonate and low energy carbonate as seen in cross plot between Qp and VpVs (figure 2c). High energy carbonate facies have higher Qp value ranging from 2.5–45 (see figure 2a) while low energy carbonate has Qp value of less than 2.5 (See figure 2b). In high energy carbonate, low water saturation reservoir is easier to recognize from cross plot in figure 2a with Qp ranging from of 10–18 and VpVs ranging from 1.4–2.

![Figure 1. Petrophysical analysis result and its estimation of attenuation.](image)
Low water saturation cluster on high energy carbonate has same range as gas or condensate bearing reservoir from Klimentos (1995) where it has Qp range 5–30 [2] and 12–18 with Vp/VS ratio 1.5–1.7 [9]. Although, in low energy carbonate facies, there is no clustering between hydrocarbon-bearing reservoirs and wet reservoir rocks as seen in figure 2b.

Zhang et al method can be well implemented to predict attenuation in P-waves than S-wave [3]. It is possible from multiple linear regression to P-wave has a higher correlation and determination coefficient compared to the equation for wave S. The log result can be seen in figure 1. In high energy carbonate facies, Qp values range from 35–210 while Qp values for low energy carbonate facies range from 30–155. In other hand, Qs values range from 490–7570 in high energy carbonate facies while Qs values for low energy carbonate facies range from 550–4800. By using this method, estimated Qs value looks overestimate because Q value for sedimentary rock is below than 200 [12].

Figure 2. The cross plot between Vp/VS ratio and Klimentos and McCann [8] P-wave quality factor on (a) high energy carbonate facies, (b) low energy carbonate facies, and (c) all lithofacies. Point color means water saturation.
It may lead biased interpretation by using this Qs value. In high energy carbonate facies, Qp value for high saturated gas reservoir with 20–40 % water saturation has the lowest Qp which ranges from 30–50 with VpVs ratio 1.5–2 (see figure 3a). Qp value increase gradually as the water saturation increases. Whilst there is no water saturation cluster for low energy carbonate, so this facies is less likely to discriminate hydrocarbon bearing reservoir with wet reservoir as seen on figure 3b.

By using 3 equations from Mavko et al.’s method, QsQp ratio was estimated by using 3 different equations. The result can be seen in figure 1 and table 1. According to that, QsQp ratio is less sensitive to identify hydrocarbon reservoir. It is showing wide range value of QsQp ratio. However, low energy carbonate has lower value and narrower range of QsQp ratio than high energy carbonate. QsQp ratio is more sensitive to identify reservoir and non-reservoir lithology such as shale. Shale has high QsQp ratio with 100 % shale volume and water saturation. In contrary, in Malay Basin field, QsQp ratio can be used to identify fluid content [13]. The QsQp ratio anomaly is similar to high gas saturation while low QsQp ratio is match to shale or wet reservoir.

![Figure 3](image_url)

**Figure 3.** The cross plot between VpVs ratio and Zhang and Stewart’s [3] P-wave quality factor on (a) high energy carbonate facies, (b) low energy carbonate facies, and (c) all lithofacies. Point color means water saturation.
Table 1. The summary of QsQp ratio of Mavko method.

|                | High energy carbonate | Low energy carbonate | Hydrocarbon reservoir | Shale |
|----------------|------------------------|-----------------------|-----------------------|-------|
| QsQp           | 0–90                   | 0–50                  | 0–90                  | 35–50 |
| QsQp2          | 0–10                   | 0–5                   | 0–10                  | 4–12  |
| QsQp3          | 0.8–18                 | 0.8–10                | 0.8–18                | 8–15  |

Figure 4. The cross plot between SQp and SQs on (a) high energy carbonate facies, (b) low energy carbonate facies, and (c) all lithofacies. Point color means water saturation.

The estimated inverse scaled-Q factor proposed by Hermana et al can be seen on figure 1. It is showing similarity trend to first theorem of QSQp ratio method. Hydrocarbon identification is interpreted by plotting SQp and SQs value. As seen on figure 4c, SQp and SQs method are changing
gradually as the reduction of water saturation. High gas saturation with 20–40% water saturation has SQp value ranging from 0.05–2 and SQs value ranging from 0.6–0.75. Wet reservoir has SQp value ranging from 0.05–2 and SQs value ranging from 0.48–0.55. Compare to Malaysian Offshore case, the hydrocarbon bearing reservoir has SQs value 0.6–0.7 and SQs value 0.6–0.9 while wet reservoir has SQp value 0.6–0.8 and SQs value 0.4–0.65 [14]. It means that SQs value is sensitive to detect water saturation and hydrocarbon indication. By this method, lithofacies does not give any impact to discriminate hydrocarbon indication. As seen on figure 4a and 4b, both lithofacies are showing gradual change as the reduction of water saturation as the increasing of SQs value.

Facies and amount of water saturation affect the result of the estimated rock quality factor. Low energy carbonate will tend to produce irregular attenuation value than high energy carbonate one. This becomes possible due to the high content of shale indicating poor quality and higher water content. Low gas content may give no or little effect to carbonate elastic moduli and wireline log reading even though fluid effect in carbonate rock is still debatable [15]. This will make the discrimination of hydrocarbon bearing reservoir and wet reservoir become harder. Conversely, in low water saturated reservoir, the presence of high gas content within reservoir affects elastic moduli of carbonate. It directly gives some effects to the result of estimated rock quality factor as seen on Klimentos method, Zhang method, and Hermana Method. So that, it can be easier in discriminating fluid content.

4. Conclusion

This study result is to estimate and compare the characteristic of seismic wave attenuation in carbonate rock reservoir of Kujung I Formation. All methods except Qs from Zhang method are applicable to estimate attenuation in carbonate reservoir. Klimentos, Zhang and Hermana methods are sensitive to identify hydrocarbon. High energy, clean carbonate reservoir tends to be more sensitive to hydrocarbon indication. A new understanding of attenuation characteristic in carbonate reservoir contributes to new methodology in discrimination pore fluid for hydrocarbon exploration.

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