Identifying Pore Type of Lagoon and Barrier Carbonate to Model Shear Wave Velocity by Differential Kuster-Toksöz Case Study in Salawati Basin

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Abstract

The shape of pores in sedimentary rocks is dependent on the geometric structure of the rock matrix grains. Carbonate rocks have more complex pore types compared to clastic due to the effects of diagenesis and the depositional environment. The study analyzed the deposition of Kais carbonate in barrier and lagoon environments. It categorized the pores into inter-particle, moldic/vuggy, and micro-cracks. The type of pore in a rock is directly related to its stiffness and shear resistance, which influences its shear wave velocity (Vs). Thus, a higher shear modulus leads to a higher Vs value. Reservoir characterization heavily relies on the Vs data. However, this data is limited to the observed area. Therefore, Vs modeling is a more effective and efficient approach. The modeling will conduct thoroughly with the identification of the pore type. The rocks moduli are calculated by the pore inclusion method using the differential Kuster-Toksöz (DKT) equation and defining the aspect ratio, reflecting the pore type. The YP-1 well has barrier carbonate, while YP-2 and YP-3 have lagoon carbonate with inter-particle as the primary pore type. Micro-cracks on top of Kais are present. YP-4 and YP-5 have similar proportions of micro-cracks and inter-particle as dominant pore types. The predicted Vs and measured logs strongly correlate with an $R^2$ value above 0.8. The Vs value range for micro-cracks is 2,300 ft/s to 6,000 ft/s, and for inter-particle, it is 6,000 ft/s to 8,500 ft/s. Pore types above 8,500 ft/s are very stiff (moldic pore type).

Keywords: barrier carbonate, carbonate pore type, lagoon carbonate, Vs prediction

1. Background

The Salawati Basin, West Papua, is one of Indonesia's most productive hydrocarbon basins [1]. Oil was produced from the Kais carbonate reservoir at the Miocene age with source rock from Kais Fm. and Klasafet Fm. Since then, the Salawati Basin petroleum system has been worked and well defined in tertiary play type [2]. Livingstone et al. [3] compared the reservoir properties of the Kasim and Walio field in 1992. The Walio field is a giant oil field in Salawati Basin, which is covered by 297 wells, and 238 wells are oil producers of 10,160 barrel per day (BOPD) [3].

Researchers have utilized new data to enhance their understanding of Kais carbonates through sedimentology and paleogeography studies [4]. In addition, the Salawati Basin has undergone extensive research on its stratigraphy and tectonic history [5]. The study also included an analysis of potential source rocks and reservoirs, utilizing 1D basin modeling to examine pre-tertiary sources [6]. Furthermore, geochemical data from oil seeps were used to evaluate younger-tertiary source rocks [7]. Seismic advance studies were conducted in various areas of the Salawati Basin, including the Walio field [8], the "P" field [9], and the gas field [10]. Extensive study has been conducted by several experts on the regional geology and reservoir characterization of the Salawati Basin. However, recent data and methods make this basin still appealing to study.

The reservoir characterization is the main factor analyzed in developing the geological model. Moreover, the reservoir's ability to trap the hydrocarbons is related to the reservoir quality (i.e., porosity and permeability) [11]. The carbonate reservoir is a porous and permeable sedimentary rock that contains hydrocarbon, with approximately 60% of oil and gas production worldwide [12]. The pores present in sedimentary rocks are determined solely by the geometric structure of the grains in the rock matrix. The
carbonate pore type is the final stage of the combining effect of various geological episodes. That is the depositional environment and rock diagenesis with several change episodes during the burial history [13]. The observed carbonates were deposited in the lagoon and carbonate barrier areas, with three pore types: inter-particle, moldic/vuggy, and micro-cracks/fracture.

The pore system in carbonate rock is more complex than in clastic rock. Its seismic velocity response can significantly affect it, as mentioned in reference [14]. Solid materials can transmit both compression and shear waves, but only P-waves can travel through fluids. Thus, the S-wave identifies the rock’s rigidity or stiffness. Rocks with predominantly rounded moldic and vuggy pores are more rigid and compressible, allowing seismic waves to travel faster than rocks with inter-particle pores. Conversely, rocks with mostly flat micro-cracks are weaker and cause seismic waves to travel more slowly. Saturated/unsaturated carbonates pores also respond differently to rock density and elastic moduli [14]. Furthermore, refer to refer to Castagna’s study [15], the carbonate rock’s final porosity product will impact the nonlinear relationship with compressional wave velocity (Vp) and shear wave velocity (Vs).

Reservoir characterization is an essential process for understanding the properties of a reservoir. Acoustic log data, specifically Vp and Vs values, are analyzed to produce a quantitative seismic interpretation (QI) that determines the reservoir’s fluid type and properties and evaluates fractures [16, 17]. The values of Vp and Vs rely on the density and elastic moduli of the rock formation. However, the oil and gas industry has limited Vs measurement data, and obtaining more data would be prohibitively expensive [18]. Additionally, the acoustic log data from open-hole wells does not apply to existing wells [19]. A cost-effective solution to this issue is developing a shear wave model.

The shear wave estimation method was introduced in early ’80 and performed on a clastic medium (sandstone reservoir) [20]. Then the formula was modified by Xu and Payne in early ’90 to be applied on carbonate rock. Thus, the methodology of this study will use the Xu-Payne model since the observed reservoir was carbonate rocks.

The elastic properties in carbonate were modeled by the extending method from the previous study of Xu and White [21]. The bulk and shear moduli equation were approximated by the equation solved by Keys and Xu [22] and substitution of a differential effective medium (DEM) on the Kuster-Toksöz (KT) equation [23]. Candikia et al. [24] and Amini [25] proved that the classical DEM is a delicate method to calculate inclusion (each pore type) which adds to the host rock. Liu et al. [26] have used the methodology of Xu and Payne and named with differential Kuster-Toksöz (DKT). They result shows classical KT and DEM method was shortly to differentiate the moduli elastic since it considers multiple porosities and higher porosity of host rock. Then, it proved that the DKT method was superior to KT and DEM methods. It can simultaneously perform on various pore types [26, 27]. While calculating the rock moduli, the aspect ratio of the geometrical shape of grains was introduced to the system on the DKT equation. This aspect ratio represents the rock’s pore type.

This study aims to construct a robust Vs model by thoroughly examining and identifying the various pore types existing within the carbonate rocks.

2. Methodology

Geographically, the area of study is located in the western part of the Bird Head’s region of West Papua, Indonesia. The geological setting of the Salawati Basin is situated at the northern margin of the Indo-Australian Plate, with Ayamaru platform in the northern area, Bintuni Basin in the southwest, and also Misool-Onin Geanticline to the south [4]. The Sorong Fault zone is a sinistral strike-slip fault with a total length of 1,900 km along the Banggai area from East Sulawesi to the north of Papua [5]. The fault caused the primary tectonic setting in Salawati Basin in the Pleistocene era. The fault has more than one splay of the strike-slip fault and S-N normal fault trend.

The proven reservoir in Salawati Basin was Kais carbonate deposited in the Middle to Late Miocene. During this period, the sedimentary rock deposits were carbonate rock. The sea inundated almost all the emergent areas of the Salawati’s basement, including the northern landmass. The carbonates were deposited during progressive northward transgression [5]. The overlaid
formation is a proven source rock and effective cap rock, the generalized stratigraphy of Salawati basin was illustrated in Figure 1. The migration pathway is along the nose structure and fault as a conduit during the migration. Most of the patch reefs are fabricated to the southern area of the basin in the recent carbonate environment [5]. Figure 2 depicts the carbonate depositional environment in the study area, which focuses on the lagoon and the barrier carbonate area as reference data. The lagoon environment consists of the pinnacle reef geometry, and the platform environment is the build-up carbonate geometry.

Studies have classified pore spaces into two categories: clay and non-clay pores [8]. Three types of pores fill the non-clay pores: inter-particle is the most pore type in carbonates, then micro-cracks which is the most compliant component in carbonate, where the crack’s porosity depends on the effective stress. Furthermore, the velocity will go faster through the stiff pores while becoming slower through the micro-cracks of carbonate rocks [13].

This study focuses on the three types of pores: moldic (vuggy), inter-crystal (inter-particle), and micro-cracks; or with geophysical terms sequentially with stiff, reference, and cracks. Several researchers [9, 28] also carried out a shear wave model using a similar method in the Salawati Basin, and other basin in East Java [11, 29, 30], which was successful with its inversion for each pore type using DEM methods. The Xu-Payne model workflow (Figure 3) consists of four steps. First, calculate the minerals present in the rocks by mixing law (e.g., the Reuss-Voight-Hill average). Second, calculating effective rock properties (e.g., bulk modulus) using differential Kuster-Toksöz (DKT). Third, the remaining water, not bound to microspores, is calculated with Woods’s law to be mixed with oil or gas. Ultimately Gassmann’s equation is to add mixing fluid into the pore system.

Table 1 is available data in the study area, which consist of measurement (√) and interpretation (ο) of log data, and some log data is not measured (x). Five wells are complete data of GR, Vp, and density. However, the Vs is only available in the YP-1 well. The YP-1, YP-4, and YP-5 are the production wells, and the other two are exploration wells (P&A with trace oil show).
Figure 3. The workflow diagram for Vs and Vp prediction.

Generating pseudo-S-wave used a rock physics model adapted from the Xu-Payne model. The model represents the various pore types in carbonate rocks, which will impact the velocity. The pore types divide into four-pore types: clay-related pores, inter-particle pore, micro-cracks, and stiff pores [13]. Afterward, the relationship of total pore expresses with the below equation:

$$\phi_T = \phi_{Clay} + \phi_{IP} + \phi_{Crack} + \phi_{Stiff}$$  \hspace{1cm} (1)

where:

$\phi_T$ = Total porosity (%)

$\phi_{Clay}$ = Clay porosity (%)

$\phi_{IP}$ = Inter-particle porosity (%)

$\phi_{Crack}$ = Crack porosity (%)

$\phi_{Stiff}$ = Stiff porosity (%)

This method assumes that interconnected macropores, such as those found between particles, have a high enough permeability to equilibrate pore-pressure differences within half a seismic wave cycle. However, due to their small size, water-wet and isolated micropores will exhibit a high-frequency seismic response. In addition, the laboratory data (e.g., oil gravity, GOR (Gas Oil Ratio), reservoir temperature, or gradient temperature, and water salinity) was calculated on the fluid calculation.

Minerals which contained the rock matrix are calculated using Voigt-Reuss-Hill average (elastic rock modulus). In carbonate is divided into calcite and dolomite, also clay content. The equation is expressing the mixture minerals [13]:

$$\frac{1}{M_r} = \sum_{i=1}^{n} \frac{f_i}{M_i}$$ \hspace{1cm} (2)

$$M_v = \sum_{i=1}^{n} M_i f_i$$ \hspace{1cm} (3)

and the average is

$$M_{vrh} = \frac{M_v + M_r}{2}$$ \hspace{1cm} (4)

where:

$M_r$ = elastic modulus of Reuss method (pa)

$M_v$ = elastic modulus of Voigt method (Pa)

$M_i$ = $i^{th}$ elastic modulus of mineral (Pa)

$f_i$ = $i^{th}$ mineral fraction (Pa)

Differential Kuster-Toksöz, was approximated [21], expressed in the equation:

Table 1. Well log data availability

<table>
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<tr>
<th>No</th>
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<th>Vp</th>
<th>Vs</th>
<th>Rho</th>
<th>VSP/CKS</th>
<th>Por.</th>
<th>SW</th>
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<td>o</td>
<td>x</td>
<td>Production well, Vs model</td>
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</tbody>
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\[(1 - \phi)\frac{dK}{d\phi} = \frac{1}{3}(K' - K)\sum_{i=5,c}v_iT_{ijj}(\alpha_i)\]  
\[(1 - \phi)\frac{d\mu}{d\phi} = \frac{1}{5}(\mu' - \mu)\sum_{i=5,c}v_iF(\alpha_i)\]

where:

- \(\phi\) = porosity (\%)
- \(K\) = bulk moduli of the dry frame and rock matrix (Pa)
- \(K'\) = bulk moduli of the pore inclusion material (Pa)
- \(\mu\) = shear moduli of rock matrix (Pa)
- \(\mu'\) = shear moduli of the pore inclusion material (Pa)
- \(T_{ijj}(\alpha_i)\) and \(F(\alpha_i)\) = pore aspect ratio functions derived from the tensor \(T_{ijj}\)
- \(v_i\) = fractional volume of the rock matrix of clay (C) and sand (S)

The equation \(T_{ijj}(\alpha_i)\) and \(F(\alpha_i)\) are given by Kuster-Toksöz [23] and Xu and White [21]. These formulas are mathematically equivalent to Berryma’s [31] for oblate spheroids. The bulk and shear moduli of pore inclusion were calculated simultaneously, thereby providing the bulk and shear moduli of the dry frame and rock matrix. The aspect ratio of cracks ranges from 0.01 – 0.02. The aspect ratio of stiff pores ranges from 0.7 – 0.8, and the aspect ratio of inter-particle pores ranges from 0.12 – 0.15 [32]. In order to achieve the most precise fit to the measurement data, we assumed a similar aspect ratio based on the reference study and relentlessly adjusted the calculations until they were precisely accurate.

The remaining water (which is not bound to micro-pores) is mixed with the hydrocarbons (oil or/and gas) using a fluid mixing law with the Wood suspension model. And the fluid substitution by Gassmann theory [33], can be expressed as:

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

where:

- \(\phi\) = porosity (\%)
- \(K_{dry}\) = bulk modulus of the dry rock (Pa)
- \(K_m\) = bulk modulus solid mineral matrix (Pa)
- \(K_{fl}\) = modulus bulk saturated pore-fluid (Pa)

The equation (7) shows that the bulk modulus will change in response to fluid saturation level while the shear modulus remains constant. The fluid saturation effecting the rock stiffness and causing the deformation of rock bulk volume.

Based on the equation (7), the P-wave and S-wave predicted can be calculated by the following equation.

\[V_p = \sqrt{\frac{K_{sat} + 4/3\mu}{\rho}}\]
\[V_s = \sqrt{\frac{\mu}{\rho}}\]

where the \(K_{sat}\) is the saturated bulk modulus, \(\mu\) is the shear modulus and \(\rho\) is the bulk density.

3. Results and Discussion

The modeling of shear waves velocity was conducted on five wells with varying deposition environments. Figure 4 shows the depth structure map of Kais Fm, where the YP-1 well tested the barrier carbonate. YP-1 well is the reference for the Vs calibration method and is situated on the highest structure compared to the other wells. The wells in the study area were used to examine the lagoon depositional environment. This environment is known for the growth of carbonate as either a pinnacle reef or patch reef (YP-4 well) and as carbonate slope deposits (YP-2, -3, and -5 wells).

![Figure 4](image-url)
confirms the existence of inter-particle pores as the dominant pore type in the Kais barrier carbonate, represented by the blocky orange color. Moreover, vuggy/moldic and micro-cracks are also present in this well. The facies observed in this well are wackestone, packstone, and boundstone. In addition, the cementation process observed in this well will reduce the rock’s porosity.

Figure 5. The petrography analysis of the YP-1 well revealed the presence of three types of pores: micro-cracks, inter-particle, and vuggy/moldic. Also, the analysis identified the precipitation of mineral matter in the pore space, which was observed above the thin section (i.e. cementation).

The wells correlations analyze the porosity trend between all five wells deposited in different environments, illustrated in Figure 6. The blocky GR in YP-1 well indicates the carbonates grow in an almost steady environment, paleo-high base Kais. In other wells in the lagoon, the GRs suggest an unsteady environment. In some condition, reefs are drowning at a certain level (result muddy carbonate) and then grows up with good porosity [35].

Blocky porosity (i.e., the similar porosity from top to base reservoir) is illustrated in the YP-1 well, in which the carbonate grows on the high platform, and the energy of sea level rises is more steady than on the lagoon area. However, the upper Kais shows low porosity in all wells on both depositional environments due to the regional drowning carbonate era in the late Miocene time. Alternating porosity is a characteristic of wells in the lagoon environment. The YP-5 well, a carbonate slope deposited, has a high streak of porosity at the upper and lower Kais; also, tight carbonate in between.

Figure 6. In order to analyze the porosity trend, it is imperative to correlate wells from the barrier carbonate to the lagoon mound reef, which is flattened on top of the Kais Formation. The YP-1 well, a carbonate limestone deposited in the barrier carbonate, exhibits a blocky porosity trend with a thin tight zone. Conversely, wells deposited in the lagoon area display a high variation of porosity trend due to the unsteady energy of the sea level.

Figure 7. Porosity and Al cross-plot manifest a negative correlation which limestone and dolomite carbonate rock has a difference of trend in porosity and Al.
This well-characteristic possibility of micro-cracks of pore type at upper and below Kais, which are blocky high porosity, indicates inter-particle pore type. The YP-4 is the pinnacle reef showing high streak porosity in the middle and tight below Kais. The rock’s diagenesis is the main factor impacting the carbonate pore type. Porosity and Al (acoustic impedance) cross-plot of Figure 7 manifest a negative relationship, which different trends on limestone and dolomite carbonate rock.

The narrower standard deviation of Al value on limestone carbonate than dolomite in this case of study is due to the wide range of porosity in the observed dolomite rock [35]. It has also been proved by Rafavich et al.’s study about the relationship between acoustic properties and petrographic character in carbonate rocks [36]. Limestone has a higher gradient than dolomite expressed on the linear regression of limestone’s equation; y is the porosity (fraction) and x is the Al (ft/s * gr/cc):

\[
y = -1.24 \times 10^{-3} x + 0.55 \tag{10}
\]

and the dolomite’s linear regression:

\[
y = -6.87 \times 10^{-3} x + 0.38 \tag{11}
\]

However, it shows a similar indication of pore types in dolomite and limestone (calcite) for both depositional environments. The porosity is the primary factor that influences Al (P and S-impedance), and the mineral composition in carbonate (e.g., calcite and dolomite) has no significant influence on seismic velocity (acoustic properties) [36]. As seen in Figure 6, the porosity in dolomites is lower than limestone. The dolomite carbonates dominate the wells in the study area since the Miocene era topographic shows that the sea level rises suddenly, and the carbonates drown (i.e., tight upper zone in the log’s character in the lagoon area).

The YP-1 well is a carbonate limestone bank deposited, with a porosity range of 0.15 to 0.25, dominant with interparticle. The secondary is the micro-cracks pore types. The modified parameter in the minerals mix parameter and Wood’s law for fluid contains the core data information (e.g., matrix density, salinity, and gradient temperature).

The analysis cross-plot of Vp and porosity using the Xu-Payne template result that most of the re type in the YP-1 well is interparticle (Vp = the reference pore type). Some data fall into micro-cracks of pore type (Vp < the reference pore type) illustrated on Figure 9. The Vs value range on the inter-particle pore type was 6,000 ft/s to 8,500 ft/s, the micro-cracks was below 6,000 ft/s and some point was fall to the stiff pore, with Vs higher than 8,500 ft/s.

The validation result represented the high correlation from the measurement data with the model on both density log ($R^2 = 0.85$) and Vs log ($R^2 = 0.89$) data, illustrated in Figure 10. The measurement data from the process is iteratively for adjusting the Vp model by changing the aspect ratio of calcite, dolomite, and clay content, completing workflow how to QC-ing the result on Figure 8. Optimizing the Vp data increased the accuracy of the Vs prediction. Correlating the density data, as an output from the model determines the Vs prediction’s accuracy. The Vp data is optimized by adjusting the value to the Vp data measurement. Scattered data from the trend line (purple color clustered) is due to the high GR at upper Kais. High density responds to mudstone carbonate.

![Figure 8. The workflow for quality control of Vp, Vs and density predicted logs.](image)

Figure 8. The workflow for quality control of Vp, Vs and density predicted logs.

The YP-2 well, a carbonate slope where dolomite rock is deposited, has predominant interparticle pore type and micro-cracks in the upper and some in the middle Kais Fm. Some data indicate the stiff pore type at the bottom of the Kais Formation, which is penetrated by the well. The Vs predicted with validation on the density log data, since the Vp data used for adjusting the model. As seen in Figure 11, illustrates that the measurement data (black) and predicted density (blue) coincide
with \( R^2 = 0.89 \). The YP-3 well shows the validation up to 0.93, with interparticle pore type still the dominant (see Figure 12). The YP-2 and YP-3 wells have a porosity range of 0.06 to 0.18.

Figure 13 shows the YP-4 as a pinnacle reef. The micro-cracks pore type was the dominant pore type, with porosity up to 0.25. Furthermore, hydrocarbon was produced in this interval. Interparticle pore type only appears below Kais. The predicted data (red curve) coincide with the measurement data (black), and the validation result was 0.91 for predicting density data.

![Figure 9](Image.png)

Figure 9. The YP-1, a reference well to validate the S-wave model generation, manifests a good correlation qualitatively. The predicted S-wave coincides with measurement data (red and black curves coincide). \( V_p \) versus Porosity cross-plot, interparticle pore type is dominant (orange clustered), and another pore type is micro-cracks, and small amount.

![Figure 10](Image.png)

Figure 10. Validation cross-plot of density and S-wave (Vs) data between measurement and predicted results in \( R^2 > 0.8 \).
Figure 11. The YP-2 well present the predominant interparticle pore type, with micro-cracks at upper Kais. The good correlation in between predicted and measurement data shows with correlation $R^2 = 0.89$.

Figure 12. The YP-3 is presenting the good correlation between predicted and measurement data up to 0.93, with inter-particle as the dominant pore type.
The predicted data in well YP-5 was almost a hundred percent match, and the well was also dominant with micro-crack at upper Kais with porosity up to 0.25. The inter-particle pore type below Kais, as seen in Figure 14. The well tested a carbonate slope deposited with a high fault zone, similar to well YP-4. Research by Liu et al. [24], the predicted S-wave velocities using the DKT model gives high correlation with laboratory data and the results derived from DKT model superior to the data resulted by the KT model, especially for samples with high porosity.

Figure 13. The YP-4 (pinacle reef) shows the dominant pore type is a micro-crack on the upper Kais and inter-particle below Kais. The production zone at micro-cracks pore type.

Figure 14. The YP-5 illustrates the carbonate slope deposit with micro-cracks as the dominant pore type. The porosity range < 0.1 to > 0.3. Stiff pore type at upper Kais Fm. The logs prediction coincides with measurement data, and correlation $R^2 = 0.99$. 

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The Vs range values for different types of pores were as follows: micro-cracks pores ranged from 2,300 ft/s to 6,000 ft/s, inter-particle pores ranged from 6,000 ft/s to 8,500 ft/s, and stiff pores were above 8,500 ft/s. The data in the left picture shows that barrier and lagoon carbonate have inter-particle pores as the dominant pore type. On the other hand, the right picture shows lagoon carbonate with both dominant pore types (inter-particle and micro-cracks).

Figure 15 clearly displays the Vs data range for each pore type. Inter-particle is the dominant pore type for both barrier and lagoon carbonate on the left side. On the right side, lagoon carbonate has two dominant pore types: micro-crack and inter-particle. It is important to note that micro-cracks had a Vs range of 2,300 ft/s to 6,000 ft/s, inter-particle pores had Vs range of 6,000 ft/s to 8,500 ft/s, and stiff pore had Vs range above 8,500 ft/s.

4. Conclusion

This study has analyzed sediment deposition in two different environments - carbonate barriers and lagoons. The porosity and Vp correlation results indicate that the primary pore type in wells YP-1, -2, and -3 is inter-particle, with some micro-cracks at the top of Kais. In well YP-3, stiff pores were found in the middle and lower Kais. The YP-4 and -5 wells showed identical percentages of pores appearing between particles and micro gaps, with micro-cracks found in the upper Kais and pores between particles in the middle Kais.

The measurements were exceedingly correlated with the model based on Vs data, with an R² value of approximately 0.89 in well YP-1, and confirmed by the density correlation with R² of about 0.85. The data from wells YP-2, -3, -4, and -5 also demonstrated high log density correlations, with all R² averaging 0.9.

The Vs range values were accurately mapped in both environments, with interparticle pores having a range of Vs values between 6,000 ft/s and 8,500 ft/s, while micro-cracked pores had a value range of Vs between 2,300 ft/s and 6,000 ft/s. Pores above 8,500 ft/s were rigid or vuggy.

5. Acknowledgment

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Abbreviation

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>Vp</td>
<td>Compressional Velocity (ft/s)</td>
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<td>Vs</td>
<td>Shear Velocity (ft/s)</td>
</tr>
<tr>
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<td>Saturation Water (%)</td>
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