Near and far offset P-to-S elastic impedance for discriminating fizz water from commercial gas

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In many practical situations when the objective is to differentiate between high and low gas concentrations, using P-to-P (PP) seismic data alone may not be enough to successfully complete the task. The abrupt reduction in P-wave velocity (V_P) with the first few percent of gas controls the seismic response. Therefore, usually only the presence of gas, but not the saturation, can be detected with PP seismic. This well known physical phenomena can be modeled by Gassmann's equation, and was documented by Domenico in 1976. In contrast, density (ρ) varies more gradually and linearly with gas saturation, while S-wave velocity (V_S) does not vary much. As noted by Berryman et al. (2002), the linear behavior of ρ with saturation makes seismic attributes that are closely related to density useful proxies for estimating gas saturation. Attempting to extract and to use information about rock density from AVO analysis or inversion has not been a successfully robust approach in many cases because of limitations in data quality and type of processing required.

The use of P-to-S (PS) converted waves has been proposed as a possible solution for distinguishing fizz water from commercial gas. Specifically, Wu (2000) and Zhu et al. (2000) suggest using P-to-S reflectivity, which is an interface attribute. Landro et al. (1999) derived the "shear wave elastic impedance" (SEI) that is an intervallic attribute, assuming weak contrast and small incidence angle, using a linear approximation of R_{PS} (reflectivity of converted waves).

In this paper, we present a practical application of a PS converted waves "elastic" impedance (PSEI) formulation not limited to small incidence angles. We show how exploiting the PS AVO behavior, by combining near and mid-to-far offsets PSEI, it is possible to distinguish fizz water from commercial gas concentrations. Using statistical rock physics methods, we compare the classification success ratio of PSEI with the classification success ratio of a group of intervallic PP attributes. As we show, using PSEI for small and mid-to-far offsets simultaneously dramatically increases the probabilities of seismically discriminating areas with high and low gas saturations.

P-to-S converted waves "elastic" impedance (PSEI). In a similar way that Mukerji et al. (1998) and Connolly (1999) derived the PP "elastic" impedance (EI), we obtained an analytical expression for the PS "elastic" impedance. Here the term *elastic* is used not in the sense of full waveform inversion, but to mean inversion for different offsets. Starting from the Aki and Richards (1980) approximation for PS reflectivity (positive offsets), assuming weak contrast between elastic properties of layers and assuming the validity of convolutional model for PS converted waves, the following equations for PSEI were derived:

$PSEI\ (\theta p)=\rho^c V_S{}^d$ where,

$$c=\frac{K\sin\theta p}{\sqrt{\frac{1}{K^2}-\sin^2\theta p}}\left(2\sin^2\theta p-\frac{1}{K^2}-2\cos\theta p\sqrt{\frac{1}{K^2}-\sin^2\theta p}\right)$$

$$d=\frac{4K\sin\theta p}{\sqrt{\frac{1}{K^2}-\sin^2\theta p}}\left(\sin^2\theta p-\cos\theta p\sqrt{\frac{1}{K^2}-\sin^2\theta p}\right)$$

In the above equations, θp is in the angle of incidence (P-waves), and K is a constant equal to the V_S/V_P ratio. In practice, K can be defined as the average V_S/V_P of the zone of interest.

Choosing θp=1/K, PSEI(θp) gives a direct density estimator. However, in practice, to obtain a single density value from PSEI inverted traces is a very difficult task, principally because of the precision required in the incidence angle. Additionally, the validity of density derivation from PSEI can be compromised due to the approximate knowledge of V_S/V_P, noise in seismic data, possible processing artifacts, and imperfections of PS seismic inversion to obtain PSEI. Nevertheless, these facts only limit the possibility of deriving absolute density values. These do not preclude the potential use of PSEI to discriminate between reservoir situations where density is the key elastic property, as in distinguishing between fizz water from commercial gas accumulations.

When analyzing the behavior of exponents c and d as a function of incidence angle, it can be noticed that at near offsets (small angles) V_S and ρ terms contribute similarly to PSEI values. On the other hand, for mid-large offsets there is a "decoupling" between V_S and ρ, a fact that can be utilized in discriminating different reservoir properties. An analogous observation was discussed by Wu (2000), concerning the reflectivity of converted waves for a particular AVO (type III) case. We notice the same decoupling effect in terms of PSEI, and note that only the constant K determines the angle at which the effect is maximized.

At this point, we think it is important to make some comments about the differences in using PSEI or any other seismic attribute to attempt to solve an estimation or classification problem. If the objective is to estimate from seismic information a particular reservoir property or properties (e.g. porosity, V_P, V_S, ρ), then inconsistencies between velocities and the assumptions made to derive them either in processing or during inversion for the parameter are crucial. On the other hand, to statistically classify, identify, or discriminate between groups, those inconsistencies, though important, could have less severe effects on the final results by appropriate statistical calibration with training data, typically derived from well logs.

Log data. Using log data, we will analyze the statistical classification success rate for discriminating fizz water using PSEI. Although in the studied area, sandstones with commercial gas and fizz water have been found (showing similar PP attributes signatures), the available logs only sample fully water-saturated zones. Gassmann's equations were used to substitute in-place water by homogeneous mixtures of gas and water covering a range of gas saturations. Elastic properties of each fluid component at reservoir conditions were calculated using the Batzle and Wang (1992) equations. Effective fluid modulus and density were calculated with Reuss and arithmetic average respectively, for water saturations of 0.7, 0.5, 0.3, and 0 (Sg = 1-Sw). The original logs and the resulting logs after simulating different fluid substitutions are shown in Figure 1.

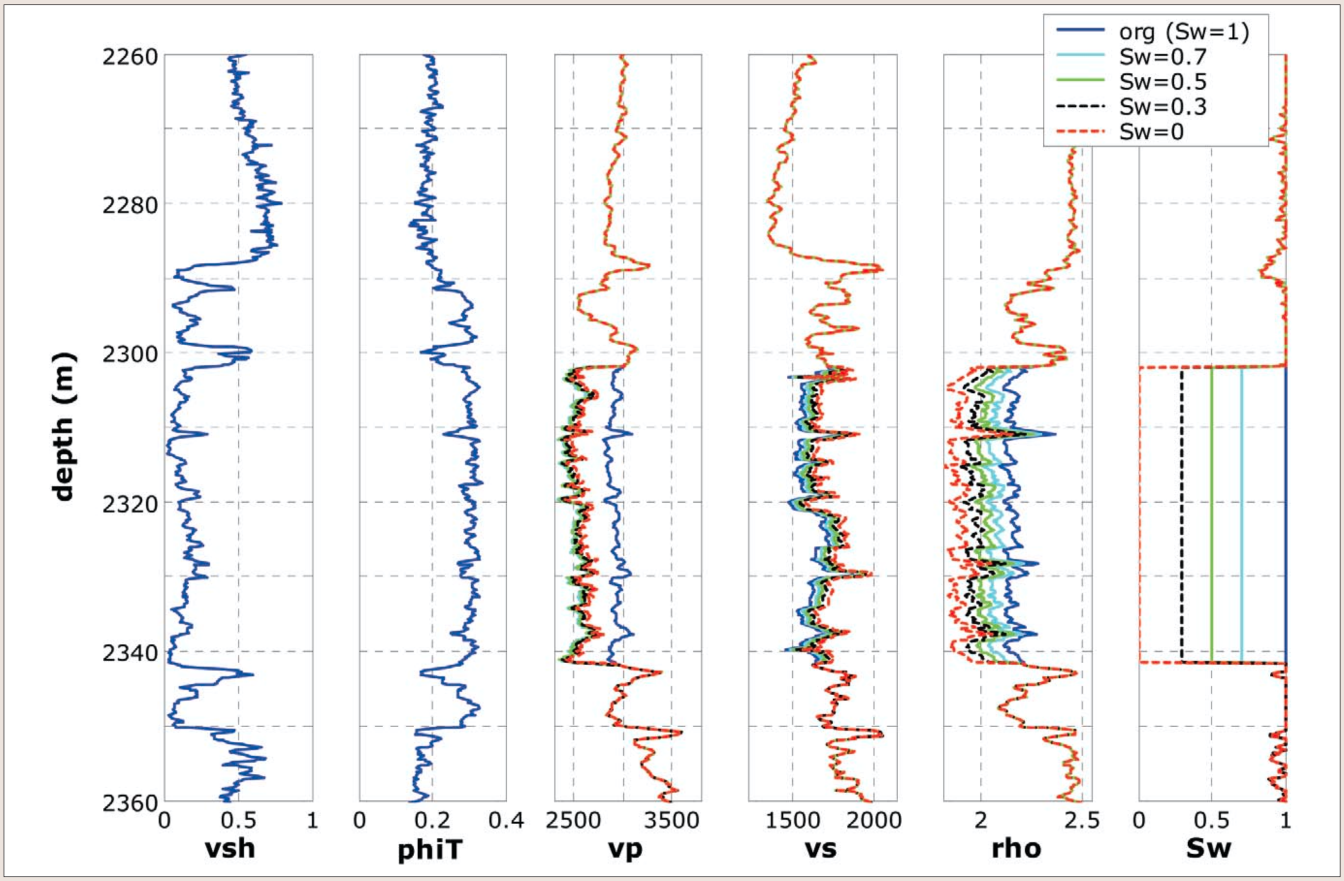


Figure 1. Original logs (blue lines), and the resulting logs after fluid substitution (Gassmann) with different water (Sw) and gas (1-Sw) saturations.

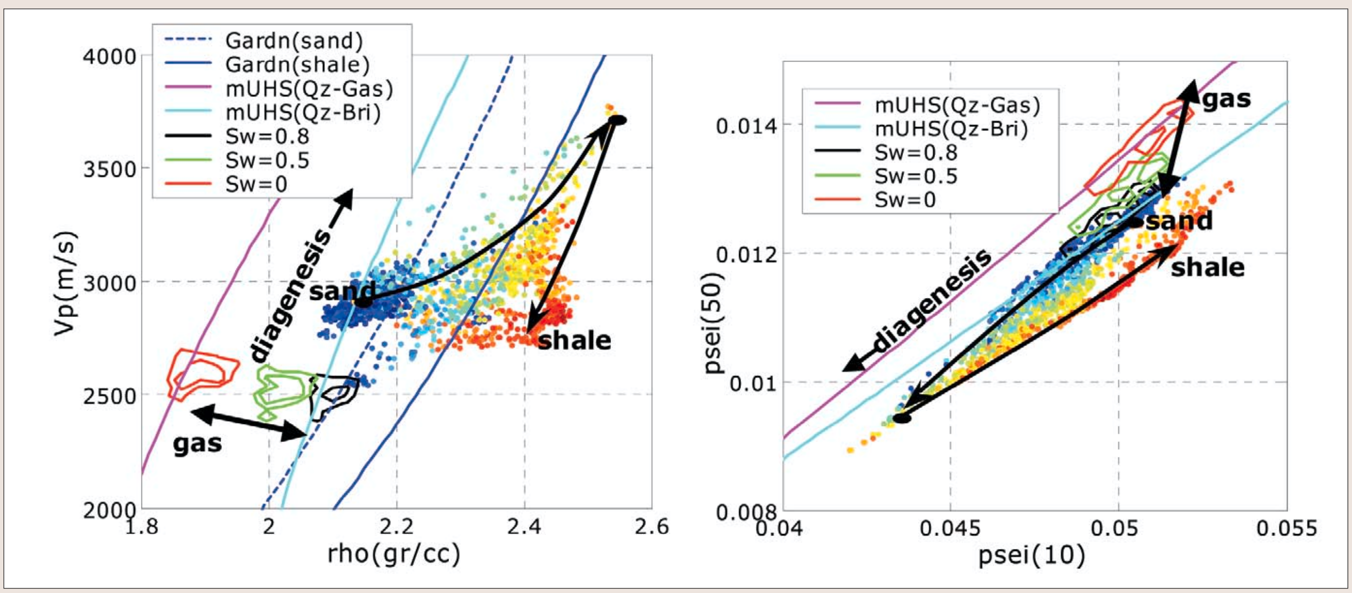


Figure 2. Density-V_P*, PSEI(10)-PSEI(50) plots. Points are log values, color-coded with the volume of shale from sand (blue) to shale (red). Contours correspond to the sands with Sw=0.8 (black), 0.5 (green), 0 (red) simulated with Gassmann's equations. mUHS: modified critical porosity upper Hashin-Shtrikman bound for Quartz and Gas (magenta) and Quartz and Brine (cyan). Black lines over the log points indicate the apparent trend for lithology change (similar to bimodal mixture model).*

Saturation and lithology trends and PSEI response. The V_P-ρ plane can be important to define parameters for seismic modeling or for rock diagnostics, even though it is difficult to directly derive them from seismic data. Usually it requires costly full waveform prestack inversion. PSEI for near and far angles of incidence are two attributes that can be derived from PS seismic data through simple partial stacked inversion. Therefore to observe and compare the behavior of well-known rock physics models in the V_P-ρ and PSEI(near)-PSEI(far) planes gives the opportunity to predict how these attributes will respond to reservoir changes such as lithology and gas saturations. For this study we chose incidence angles of 10 and 50°—approximately corresponding to offsets of 600 m and 5 km, respectively. Both

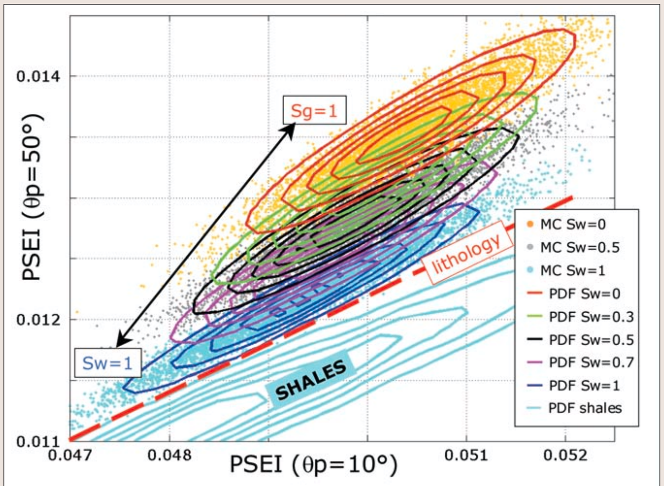


Figure 3. *PSEI for incidence angles of 10 and 50°, calculated with* V_P-V_S-ρ *drawn from correlated Monte Carlo simulations for Sw=0, 0.5, 1. Solid contours show estimated pdfs for shales, and sands with Sw=0, 0.3, 0.5, 0.7, and 1.*

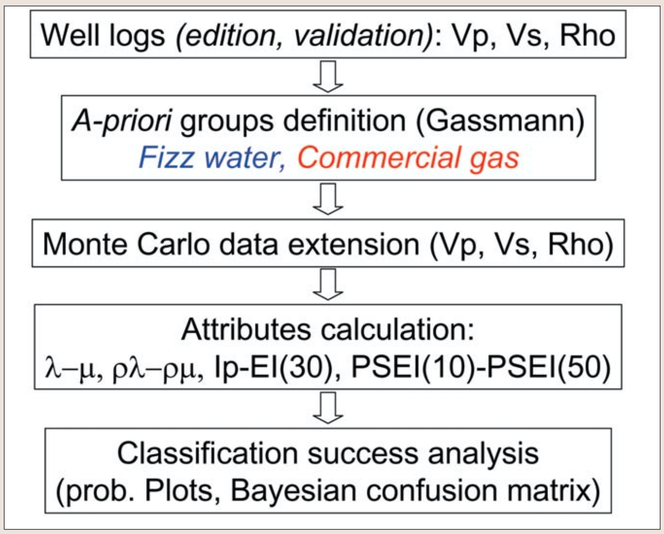
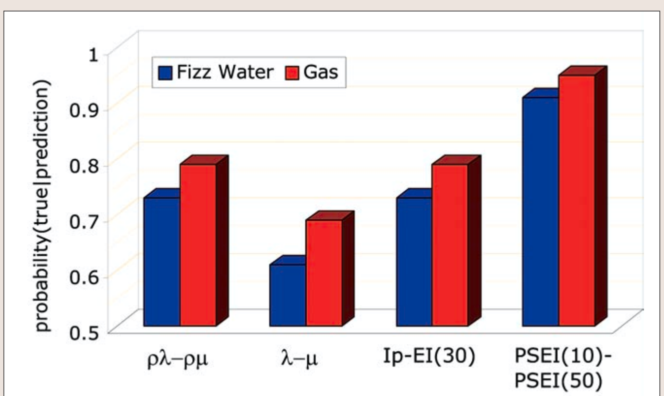


Figure 4. *Flowchart of the statistical rock physics methodology applied to compare the (Bayesian) success ratio of different seismic attributes combinations to discriminate between "fizz water" and "commercial gas."*



	Fizz Water	Gas
ρλ–ρμ	0.73	0.79
λ–μ	0.61	0.69
Ip-EI(30)	0.73	0.79
PSEI(10)-PSEI(50)	0.91	0.95

Figure 5. *Conditional probability of the true group ("fizz water," "commercial gas") given the prediction (diagonal elements of the Bayesian confusion matrix) for the four pairs of attributes studied.*

are reasonable values for current PS acquisition geometries. Figure 2 shows the log values color coded by the volume of shale, in two different domains: density-V_P, and PSEI(10)-PSEI(50). Modified Hashin-Shtrikman upper bounds (mHSU) for mixtures of quartz-gas (Qz-gas) and quartz-brine (Qz-Bri) are also plotted in each graph, with an arrow indicating the "diagenesis or depth trend." Additionally, we included contours of values calculated with Gassmann's equations, simulating the substitution of the original water in the sands by three different water-gas homogeneous mixtures (Sw=1-Sg=0.8, 0.5, 0). It can be noticed how in the PSEI(10)-PSEI(50) plane, changes in water-gas saturations are translated to clear trajectories. The points move *monotonically* in well-defined directions. Additionally, the data points seem to behave as predicted by the bimodal mixture model. Lines following this trend, from clean sandstones to pure shales, and going through the mixture, were drawn in both plots, and a clear lithology separation (shales from sandstones) can be noticed.

We extended the log data points by applying Monte Carlo (MC) correlated simulation, and calculated the corresponding probability distribution function (pdfs) for all modeled Sw situations. As can be seen in Figure 3, shales are well separated from sandstones with any Sw in the PSEI(10)-PSEI(50) plane; hence, PSEI for lithology identification is also feasible. However, the important result that we want to emphasize here is the real possibility of discriminating between different homogeneous water-gas saturations. Values of PSEI at 10 and 50° *monotonically* decrease with reduction of gas concentration, responding to changes in density. Consequently, this combination of seismic attributes has the potential to differentiate between different water-gas proportions, homogeneously mixed.

Uncertainty estimation: statistical rock physics. To compare the seismic attributes' ability to discriminate between different gas concentrations, an adaptation of Mukerji et al. (2001) methodology was applied (Figure 4). Two groups were a-priori defined: "fizz water" ($0.1 < Sg < 0.2$), and "commercial gas" ($Sg > 0.5$). Values calculated from Gassmann's theory (in the sand interval) were used to obtain each a-priori group of V_P, V_S, and ρ. Extended triples of V_P-V_S-ρ were generated with MC-correlated simulation, and pairs of intervallic attributes with well-established physical meaning were derived: $\lambda\rho$ and $\mu\rho$ (Goodway et al., 1997), λ and μ (Gray, 2002), acoustic and elastic impedance for 30° (Connolly, 1999), and PSEI for incidence angles of 10 and 50°. All these attributes are analytically defined from elasticity theory. They can be calculated from V_P, V_S, ρ log values, and extracted from seismic data. The first three pairs of attributes can be obtained from PP seismic data, and with them, PP AVO variations are included in the analysis.

We compare these attributes in terms of the Bayesian confusion matrix. The elements of a Bayesian confusion matrix give the probability of being the true group given a predicted group. In particular, diagonal elements are Prob(true group = X | predicted group = X), with X= "fizz water" or "commercial gas." For a good classification, obviously these diagonal values should be close to one. Comparing diagonal elements of Bayesian confusion matrices calculated for the four pair of attributes analyzed (Figure 5), it can be noticed that PSEI(10)-PSEI(50) was indeed the best attribute combination (among those analyzed) for distinguishing "fizz water" from "commercial gas" for the rock and fluid properties in this study area.

Conclusions. A formulation of P-to-S elastic impedance

(PSEI) was presented. The theoretical derivation assumes the validity of convolutional model for PS converted waves and weak contrast between the elastic properties across the reflecting interface. The asymmetric contribution of V_S and ρ on PSEI can be exploited in discriminating different reservoir properties, in particular high/low gas concentrations and lithology. This "decoupling" between the roles of V_S and ρ gives rise to clear trajectories in the PSEI(10)-PSEI(50) plane for changes in lithology and water-gas saturations, i.e. the points move monotonically in well-defined directions. Although, the theoretical value of the angle at which PSEI translates to a direct density value was derived, in practice, we conclude that it will be difficult to estimate densities directly from PSEI. However, this fact only limits the possibility of getting absolute density values. It does not preclude the potential use of PSEI to discriminate between reservoir situations where density is the key discriminating elastic property.

Using real well log data, we showed that increments of Sg in a homogeneous gas-water mix *monotonically* increase PSEI values. Consequently, it is possible to discriminate between fizz water and commercial gas concentration using PSEI. In the studied case, combined use of PSEI for 10 and 50° of incidence angle improve in average 20% the success probabilities of distinguishing commercial gas concentrations from fizz water, compared with the other PP seismic attributes analyzed.

One remarkable advantage of using two PSEI attributes (e.g. near and far offsets), instead of a combination of PP and PSEI is that the time and amplitude matching of PP and PS data is avoided for the interpretation.

An important question that arises after this work is how the "noise" (either processing artifacts, or random noise) affects the PSEI values or distributions. This is a very important topic in order to anticipate the areas where the discriminator potential of PSEI can be exploited.

Suggested reading. *Quantitative Seismology: Theory and Methods* by Aki and Richards (W. N. Treeman & Co., 1980). "Seismic properties of pore fluids" by Batzle and Wang (GEOPHYSICS, 1992). Combining rock physics and sedimentology for seismic reservoir characterization in North Sea turbidite systems by Avseth (PhD thesis, Stanford Univ., 2000). "Seismic properties of pore fluids" by Batzle and Wang (GEOPHYSICS, 1992). "Estimating rock porosity and fluid saturation using only seismic velocities" by Berryman et al. (GEOPHYSICS, 2002). "Elastic impedance" by Connolly (*TLE*, 1999). "Effect of brine-gas mixture on velocity in an unconsolidated sand reservoir" by Domenico (GEOPHYSICS, 1976). "Improved AVO fluid detection and lithology discrimination using Lamé petrophysical parameters; "$\lambda\rho$," "$\mu\rho$," & "λ/μ fluid stack," from P and S inversions" by Goodway et al. (*SEG 1997 Expanded Abstracts*). "Elastic inversion for Lamé parameters" by Gray (*SEG 2002 Expanded Abstracts*). "Well calibration of seabed seismic data" by Landro et al. (*SEG 1999 Expanded Abstracts*). *The Rock Physics Handbook* by Mavko et al. (Cambridge, 1998). "Compressional velocity and porosity in sand-clay mixtures" by Marion et al. (GEOPHYSICS, 1992). "Near and far offset impedances: Seismic attributes for identifying lithofacies and pore fluids" by Mukerji et al. (*Geophysical Research Letters*, 1998). "Statistical rock physics: Combining rock physics, information theory, and geostatistics to reduce uncertainty in seismic reservoir characterization" by Mukerji et al. (*TLE*, 2001). "Estimation of gas saturation using P-to-S converted waves" by Wu (*SEG 2000 Expanded Abstracts*). "Distinguishing fizz gas from commercial gas reservoirs using multicomponent seismic data" by Zhu et al. (*TLE*, 2000). TLE

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