PS wave AVO – aspects on processing, inversion, and interpretation

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Summary

Using PS wave AVO inversion, density contrasts can be obtained from converted wave data. The density contrasts are relatively reliable if the appropriate inversion method is applied. Well logs and modeling study show that density attributes are of great value to describe lithology changes and gas saturations.

Introduction

In multi-component seismic exploration, the converted wave data from P wave sources is recorded. Amplitude variation with offsets exists in converted wave data (PS wave data). It is well known that AVO is used successfully as direct hydrocarbon indicator (DHI) based on PP wave data only and AVO on PP wave data comes from rock and fluid elastic properites changes and incident angle variations. PP wave AVO applications make one consider the possibility of PS wave AVO application. To make use of PS wave AVO, a few questions has to be answered: how PS wave AVO depends on rock properties changes and incident angles; if the rock properties can be reliably inverted from PS wave AVO; how one uses PS wave AVO or inverted attributes to indicate lithology change and reservoir fluid. Following this section, reflection coefficient of PS wave will be studied at first to find out the PS wave AVO dependency on rock property changes and angles; then, PS wave AVO inversion will be discussed to elaborate the stability improvement and amplitude-preserved processing issues.

Reliable density contrasts can be obtained from PS wave AVO inversion if careful processing and robust inversion are applied on the converted wave data. To interpret the seismic-derived attributes, the rock physics study based on well logs is usually conducted first to understand the lithology separation and reservoir properties. In the paper, logs in the wells from different areas are studied to find out the advantages of density to indicate lithology change and reservoir fluid properties. Based on well log study, discussions are made on how to apply and interpret PS wave AVO attributes.

Reflection coefficient of PS wave

From Aki and Richards (1980), reflection coefficient of PS wave can be approximated as equation (1), when the elastic property contracts are small and critical incidence is not reached,

$$\mathbf{Rps} = \frac{-\mathbf{p}\alpha}{2\cos\mathbf{j}}\left[\left(1-2\beta^2\mathbf{p}^2+2\beta^2\frac{\cos\mathbf{i}}{\alpha}\frac{\cos\mathbf{j}}{\beta}\right)\frac{\Delta\rho}{\rho}-\left(4\beta^2\mathbf{p}^2-4\beta^2\frac{\cos\mathbf{i}}{\alpha}\frac{\cos\mathbf{j}}{\beta}\right)\frac{\Delta\beta}{\beta}\right], \quad (1)$$

where **p** is ray parameter, and other symbols are explained in Figure 1.

Xu (1997) re-organized equation (1) into equation (2).

$$\mathbf{Rps} = \mathbf{A}\cdot\mathbf{B} = -\frac{1}{2}\frac{\mathbf{V_P}}{\mathbf{V_S}}\tan\mathbf{j}\cdot\left(\frac{\Delta\rho}{\rho}+2\frac{\mathbf{V_S}}{\mathbf{V_P}}\cos(\mathbf{i}+\mathbf{j})\frac{\Delta\mu}{\mu}\right), \quad (2)$$

where μ is shear modulus.

Using equation (2), Figure 2 shows how the PS AVO depends on elastic properties contrasts and triangle functions of incident and converted angles. The amplitude variation with offset is dominantly controlled by the A term in equation (2).

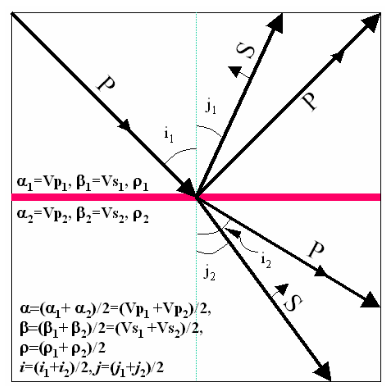

Figure 1, Plane wave propagation at an interface.

PS wave AVO processing and inversion

Equations (1) and (2) tell that reflection coefficient of PS wave reflection depends on elastic property contrasts and varies at different incident and converted angles. An inversion scheme can be formed to obtain elastic property contrast from PS reflection data. Converted wave datasets contain mainly PS wave data and can be used on PS wave AVO inversion. Like the inversion method used in PP AVO, the least-squares fitting or L1 norm fitting is usually chosen to extract contracts of Vs or μ and density. But more robust inversion methods need to be resorted to when the converted wave data is noisy.

<u>Stability of inversion</u>

In PP AVO inversion, usually two parameters (e.g. Rp, and Rs) are inverted, and simultaneous 3-parameter linear inversion through least-squares generates severe unstable solution with regular reasonable offset range. In PS wave AVO inversion, two parameters can be inverted, based on equation (1) or (2). Although the 2-parameter PS AVO inversion is somehow less stable than 2-parameter PP AVO for regular acquisition and reasonable angle range without critical incidence, it is much more stable than 3-parameter PP AVO. Usually, the least-squares fitting or L1 norm fitting is naturally chosen to extract contracts of Vs or μ and density. However, because strong noise exists on the converted data, density reflectivity solved from PS wave AVO inversion may contaminated severly by the noise through an ordinary least-squares fitting or L1 norm fitting. Therefore, PS wave AVO inversion should be handled in an more appropriate way. Some considerations are made as follows to perform the PS AVO inversion:

1. Avoid using density vs. density correlation relationships to constrain the inversion. Such kind of constraints can limit the solutions in reasonable range, but also force the density contrast to closely follow shear velocity contrast.

2. Use special techniques to stabilize PS wave AVO inversion and make the density reflectivity more reliable than an ordinary least-squares solution. Reasonable parameterization and regularization are among these techniques.

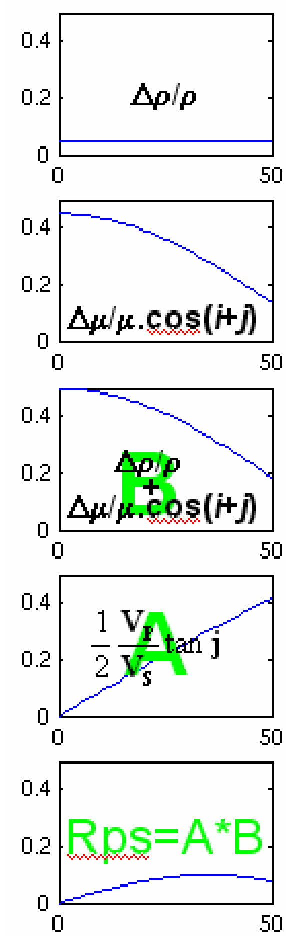

Figure 2, PS AVO autonomy (polarity ignored)

Figure 3 shows an example of PS wave AVO inversion. Incident angles from 0-50 degrees are used in the inversion. Random noise is included in the input gather. No density vs velocity relationship is used as the constraints. The inverted density and shear modulus reflectivities show reliable match with the true. Noise in the inverted attributes can be suppressed using other techniques.

<u>Amplitude-preserving concern of converted wave data</u>
Surface-consistent scaling is the very necessary step in the PP data processing to preserve amplitude for AVO analysis. Its major purpose is to adjust the trace amplitudes to surface-consistency to balance the source strength and geophone response and honor offset variation trend. With PS wave AVO, the solution of surface-consistent scaling will be dominated by AVO. To do surface-consistent scaling on the converted data, the paper suggests a method: build a background Vp, Vs grids and do PS wave ray-tracing to generate A term in equation (2) and remove A term and generate B term dataset. Surface-consistent scaling is designed on B dataset and then recover A term and apply the scaling.

<u>PS AVO inversion and Joint inversion of PP and PS waves AVO</u>

Joint PP and PS AVO inversion has been researched (Larsen, 1999). For the ideal situations, with ordinary acquisition parameters, joint PP and PS inversion may improve the stability of inversion, but not significantly. To handle real multi-component data for joint inversion, a few difficulties need to overcome:

1. To perform joint inversion, need a common domain for PP and PS data align **all** events. Sophisticated P and S velocity fields are needed.

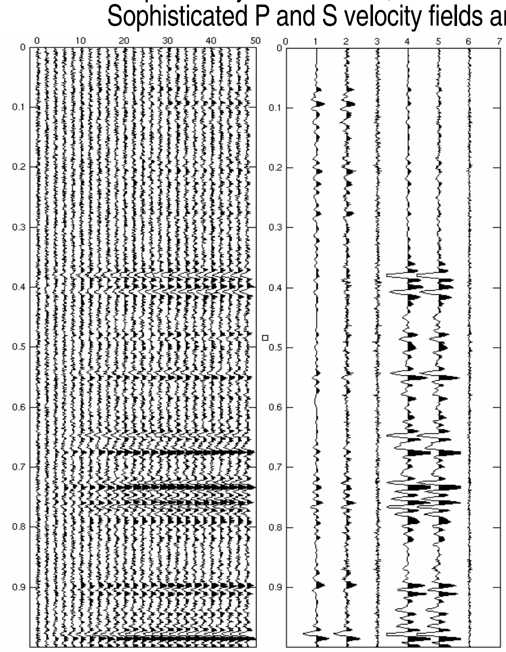

Figure 3, PS AVO inversion example. On the left panel, traces 1-6 are: true Δρ/ρ; inverted Δρ/ρ; noise in inverted Δρ/ρ; true Δμ/μ; inverted Dm/m; noise in inverted Δμ/μ.

2. Frequency band difference causes event mis-alignment on both components;

3. Separated PP and PS processing flows may use different scaling to hurt intrinsic energy partition ratio of PP and PS waves. Keeping the intrinsic partition ratio is critical for joint inversion and difficult.

Indications of density properties
Rock physics study based on well logs will provide guidelines to interpret the density and shear wave attributes from PS wave AVO inversion. Wells from different areas are selected in the following to study the well logs, mainly density log and their indications on lithology changes and reservoir properties.

<u>Observations from well logs</u>

Figure 4 shows six groups of wells from WCSB and other areas. The study in the paper is limited to clastic formations. Density logs in the wells from young or very unconsolidated formations exhibit different features from those from well-developed basin as WCSB. In the following, some observations are made based on these wells and other wells not shown.

1. In unconsolidated clastic formations, density is good indication of lithology changes and shale contents. Logs in groups A, B, C, D, and E in Figure 4 are from oil sands area in Alberta, Gulf of Mexico,

and Mackenzie Delta. Gamma ray and density logs show good resemblance and correlation.

2. In well-developed formation in WCSB, density variation with lithology in clastics is small, and the semblance between gamma and density is not obvious. However, in some reservoir formation, the density log shows strong anomaly with gas saturation. In group F in Figure 4, gas reservoir shows up clearly on the density log.

Indication of density properties

Cross-plotting is usually a good tool in rock property study. Some cross-plottings of well log in Figure 4 are done and studied. In Figure 5, gamma ray is cross-plotted with P velocity, Vp/Vs ratio and density using the well in Group D in Figure 4. Sands have lower density than shale. But ambiguity exists on Vp and Vp/Vs ratio to separate sand from shale.

In Figure 6, the Vs and density is cross-plotted based on wells from MacKenzie Delta in Group E in Figure 4. The sandy and shaly clastics formations show a slightly separated variation trends, which gives a similar view as in the cross-plots of Vp and Vs. If the reliable density and Vs constrasts are obtained, the fluid-factor like attribute (litho-factor?) can be derived from the density-Vs trend.

In Figure 7, cross-plots are made on the well logs from wells in Group F, which are from well-compacted WSCB, in Figure 4. Gas sand, wet sand, and regional shale show good separation on density domain.

PS wave AVO interpretations and applications

In the unconsolidated formation, where the density shows correlation to gamma ray. In the interpretation of attributes from PS wave AVO inversion, the density reflectivity can be used as the approximated gamma ray reflectivity. For better usage, density reflectivity can be inverted to pseudo density log, which provide better view of lithology variation in unconsolidated clastic formation. Figure 8 shows two examples of PS wave AVO inversion attributes. Figure 8 also display the synthetic gamma ray reflectivity and Vp reflectivity in PS time.

In well-compacted formation as WCSB, the density show anomaly due to gas saturation or strong porosity change. Such an anomaly can stand out on the cross-plots of density reflectivity and shear wave reflectivity and separate itself from non-reservoir or background trend. Figure 9 shows the separation of top reflections of gas reservoir, wet sand and regional shale.

Applications

Multi-component data is not as common as conventional data. Due to the high expenses in its acquisition and processing, it is necessary to fully exploit the data. Therefore, it is worth to apply PS AVO inversion. In certain plays, such as the examples used in the paper, the solutions from PS wave AVO can reduce the ambiguity in conventional seismic data and provide reservoir information not able to obtain from PP wave AVO.

More examples will be shown in the presentation.

Conclusions

With amplitude-preserved processing and right inversion techniques, reliable 2-parameter PS wave AVO inversion is possible. From PS wave AVO, density attribute and shear wave attribute can be obtained. Reliable density attributes are of great value to describe lithology changes and reservoir saturations.

References

Aki, K., Richard P. Quantitative Seismology, 1980

Larsen, Jeffrey, AVO inversion by simultaneous P-P and P-S inversion, M.Sc. thesis, 1999.

Xu, Yong, Joint AVO analysis of PP and PS seismic data. CREWES research report, 1997.

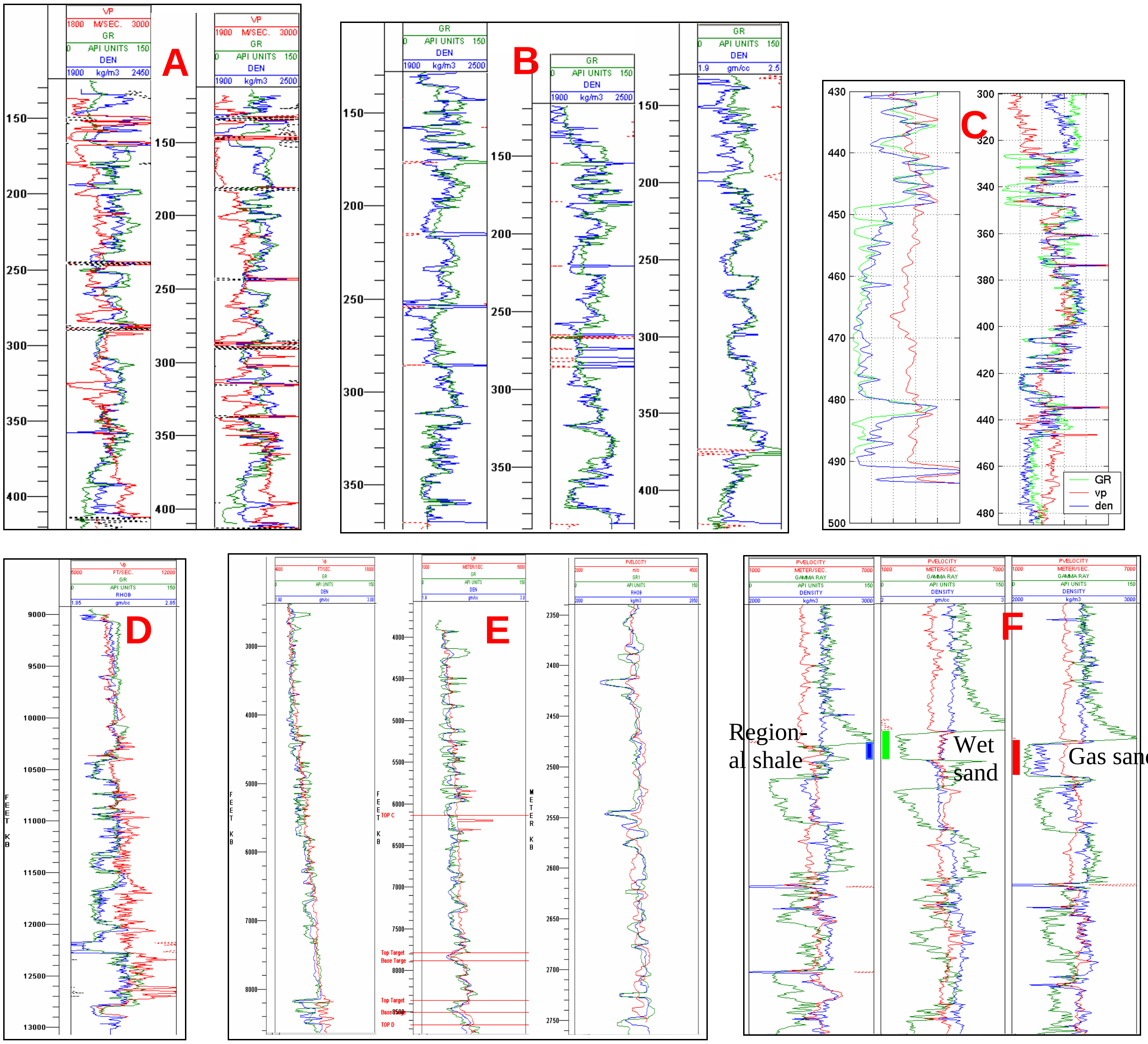

Figure 4, six groups of well logs from different areas show the relationship between gamma ray, density, and Vp. Gamma ray is in green; density is in blue; and Vp is in red. Groups A, B, and C are from three oil sands plays in Alberta. Group D is from Gulf of Mexico. Group E is from Mackenzie Delta. Group F shows three scenarios of a Cretaceous reservoir from WCSB.

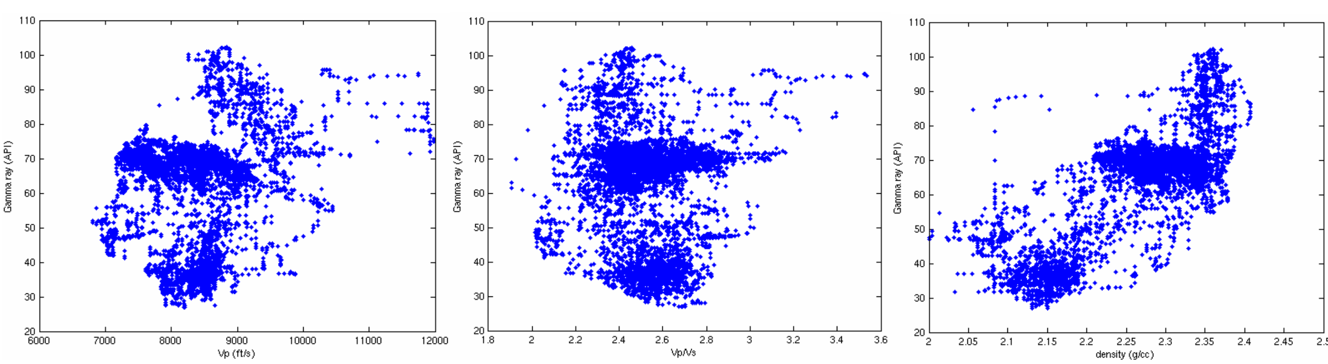

Figure 5. Gamma ray is cross-plotted with P velocity, Vp/Vs ratio, and density using the well in Group D in Figure 4.

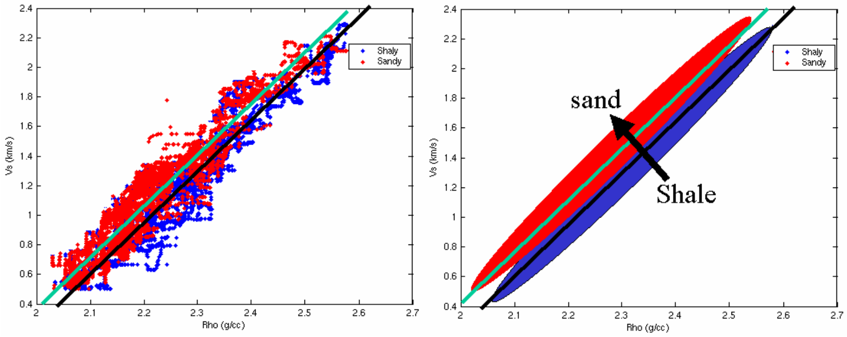

Figure 6. Cross-plots of Vs and density from wells in GROUP-E in Figure 4. Sand and shale trends are diagrammed in the right.

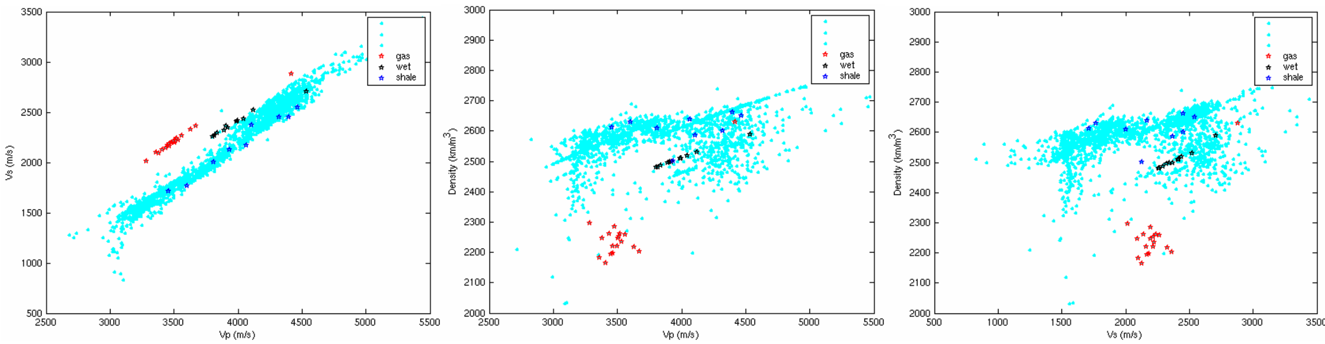

Figure 7. Cross-plots of well logs from wells in GROUP-F in Figure 4. Gas sand, wet sand and regional shale are highlighted.

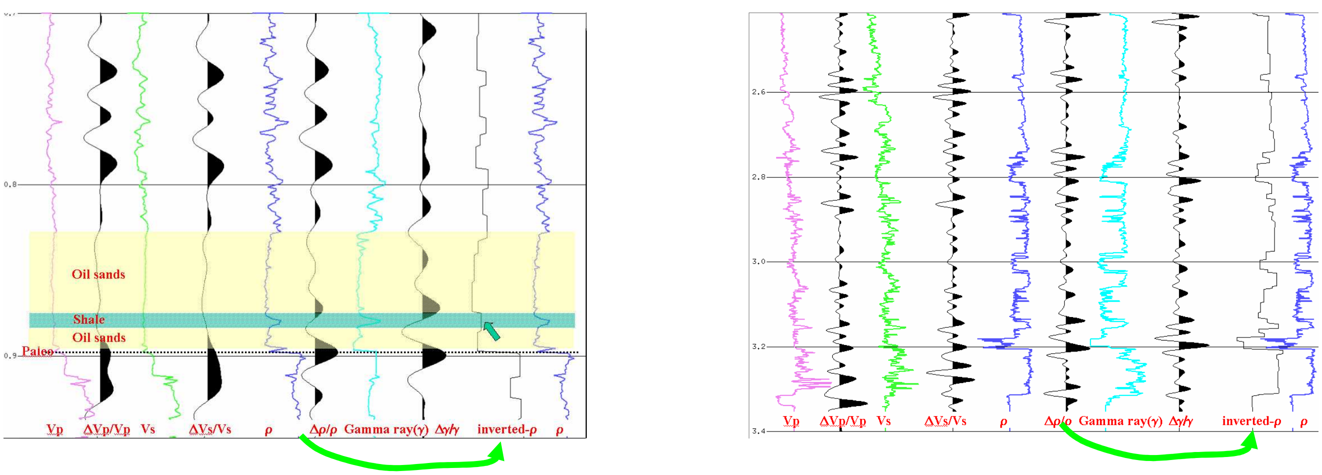

Figure 8. PS wave AVO inversion attributes: Left panel is based on a well in Group-B in Figure 4; right panel is based on the well in Group-D in Figure 4.

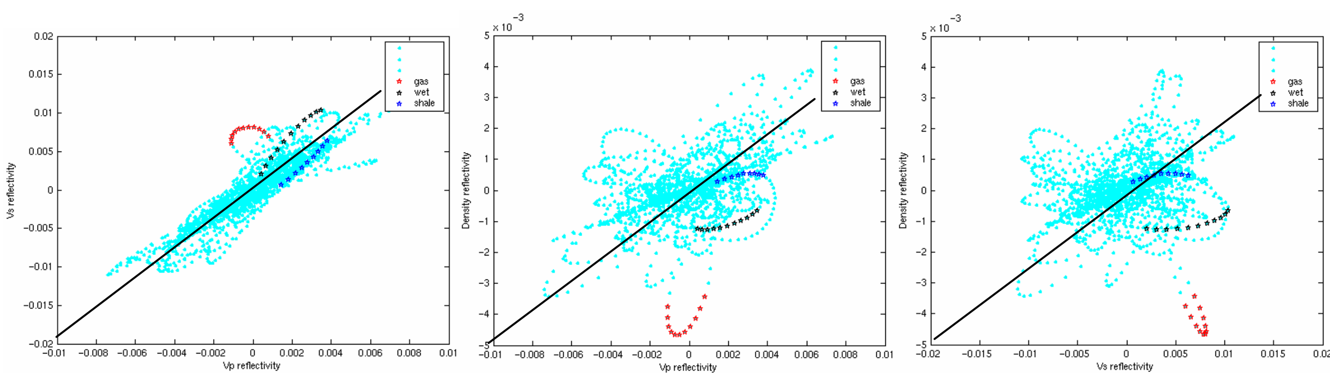

Figure 9. Cross-plots of reflectivities show different separation of wet, gas, and shale.