The anatomy of AVO crossplots

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AVO crossplots are a simple and elegant way of representing AVO data. Offset variations in amplitude for reflecting interfaces are represented as single points on a crossplot of intercept and gradient. The advantage of this type of plot is that a great deal of information can be presented and trends can be observed in the data that would be impossible to see with a standard offset (or angle) versus amplitude plot. The crossplot is an ideal way of examining differences in AVO responses that may be related to lithologic or fluid-type variations. Commonly used techniques for revealing these differences include color-coding samples from the crossplot and using this as an overlay to a seismic display or creating weighted (or "equivalent angle") stacks (i.e., linear combinations of intercept (R0) and gradient (G).

The early literature approached AVO crossplots from the point of view of rock properties. A central concept that emerged from this work was the "fluid line," a hypothetical trend based on a consideration of brine-filled rock properties together with simplifications of the reflectivity equations (Figure 1). If the intercept is plotted on the x axis and the gradient on the y axis, then for consolidated sand/shale rocks the top and base reflections form a trend from the upper left to the lower right quadrant of the crossplot that passes through the origin. When it was realized that data points for equivalent hydrocarbon-filled rocks plot to the left of this line, it became clear that normalizing the data against the fluid line might provide an optimum AVO indicator.

The similarity of the fluid-line trend to trends on time-window AVO crossplots generated from seismic was compelling, and many assumed these are the same. In fact, both models and real data examples show that

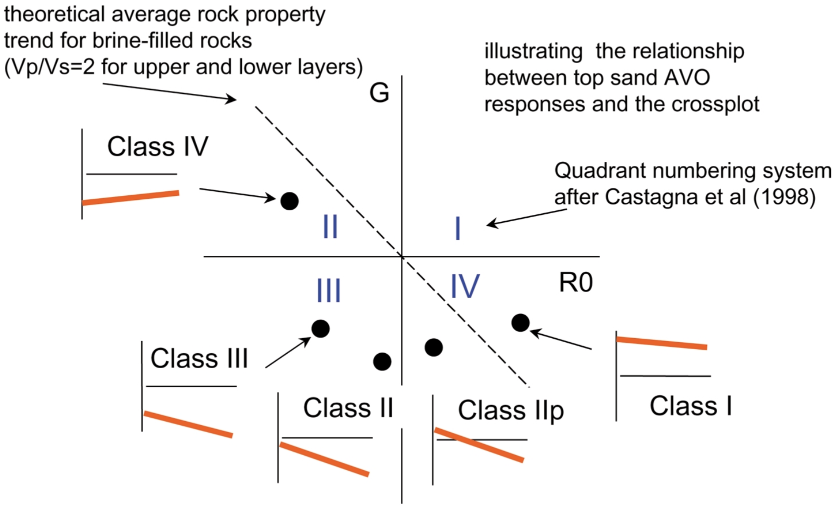

Figure 1. AVO classes and the AVO crossplot.

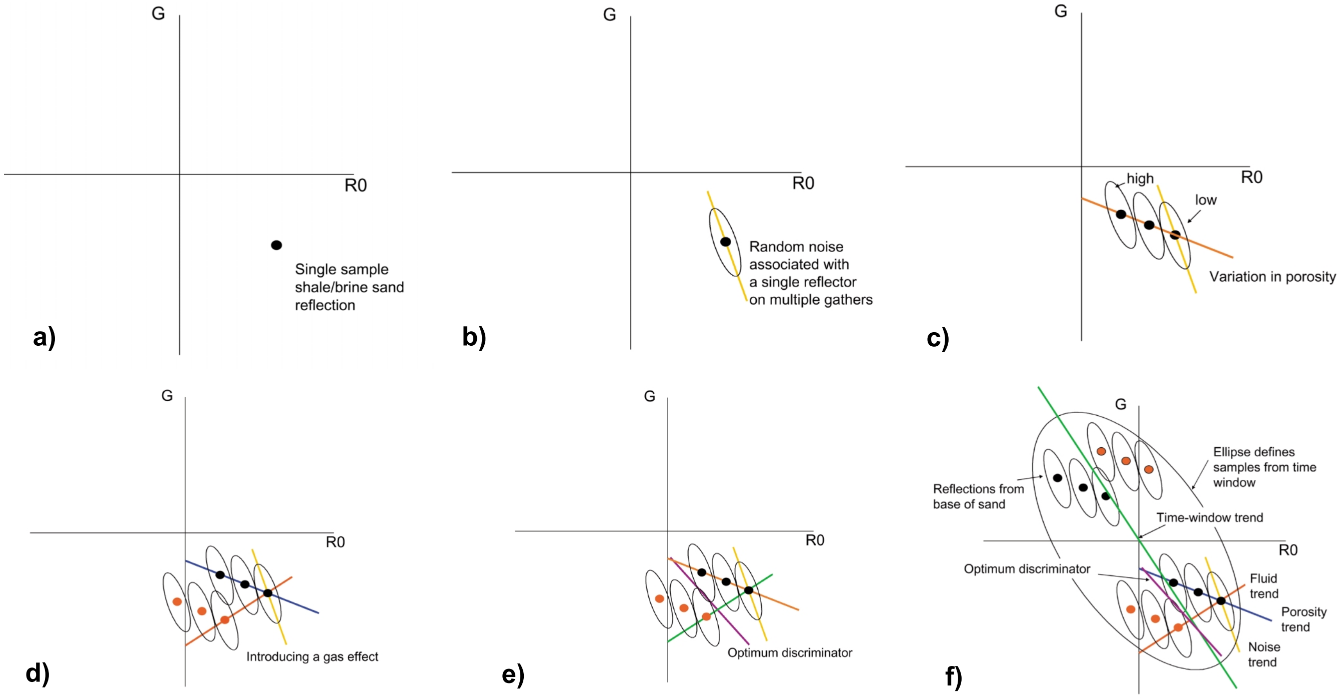

Figure 2. The anatomy of AVO crossplots. (a) A single class I reflection. (b) The noise associated with the measurement of gradient on numerous gathers. (c) The porosity effect. (d) The gas effect. (e) The optimum discriminator. (f) The time-window crossplot.

in general this is not the case. Real crossplot trends depend principally on the way the crossplot has been constructed (i.e., horizon versus time-window crossplots), the amount of noise relative to signal, and the magnitude of any effect associated with hydrocarbon (i.e., the "gas effect"). While rock-property information is contained in AVO crossplots, it is not usually detectable in terms of distinct trends, owing to the effects of noise.

Signal and noise. Consider a single point in the lower right quadrant on a crossplot (Figure 2a). This point was generated from the AVO attributes (derived by least squares regression) associated with the maxima of a single zero-phase reflection on a synthetic gather with no noise. It represents a class I response from the top of a brine-filled consolidated sand at the boundary with an overlying shale, i.e., the amplitude is decreasing with offset. This representation might be called a "horizon crossplot" as it relates to a single reflecting interface.

If data from several gathers with the same reflection are crossplotted, then the crossplot signature is of course the same—a single point on the plot. However, if random noise is added uniformly across the gathers (such that the S/N decreases with offset), the crossplot response becomes an oval distribution of points around the real location (Figure 2b). This is due to the sensitivity of the gradient estimation to noise. Hendrickson has termed this the "noise ellipse." This noise trend is easily recognized on real data, for example by crossplotting a limited number of samples from the same horizon from a seismic section. The extension of the trend parallel to the gradient axis is an indication of the amount of noise in the data. On real data the noise trend usually has a slope of about -5 or more. The effects of other types of noise (such as RNMO) will not be dealt with here.

Cambois indicated that the slope of the noise trend is dependent on two-way traveltime, velocity structure, and offset. On real data the general position of a data cluster (such as that shown in Figure 2b) is dependent on the relative scaling of R0 and G (and may be affected by residual moveout or uncorrected amplitude decay). However, the slope of the noise trend is independent of this scaling.

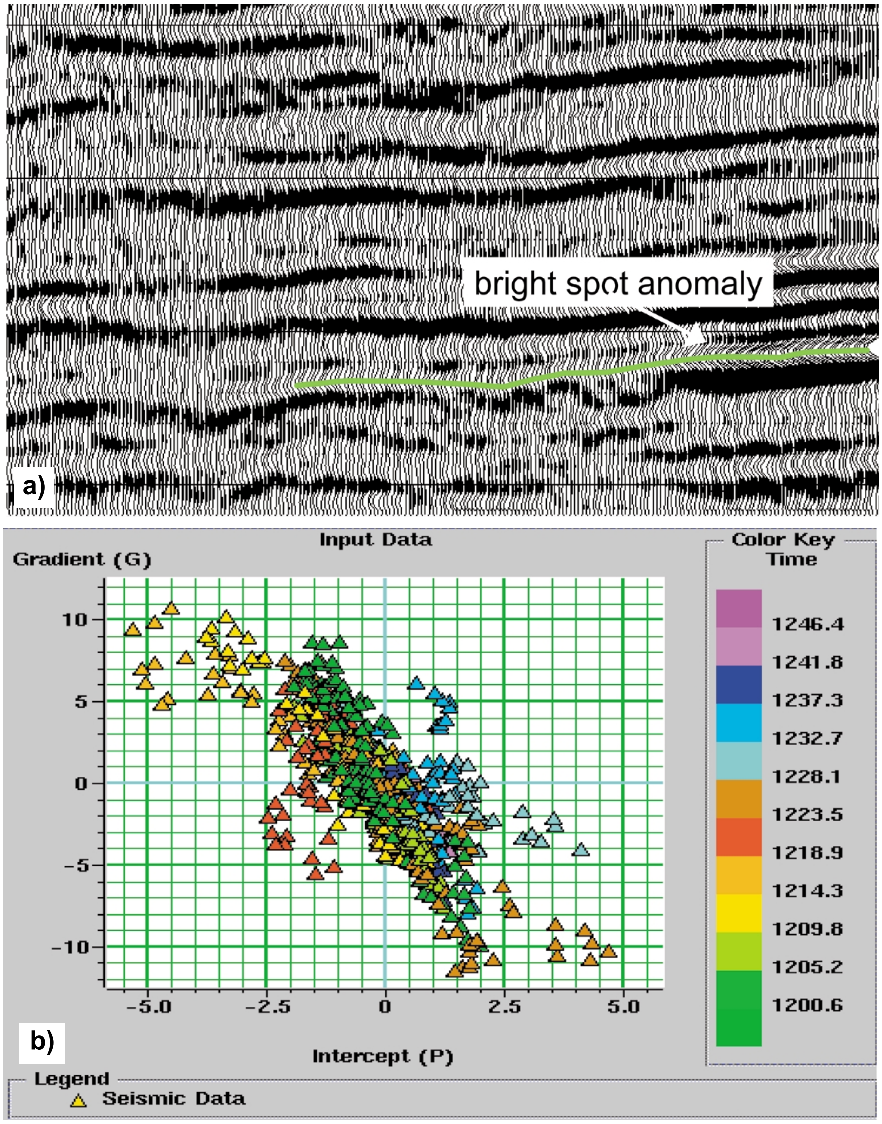

Figure 3. A real data example. (a) Stacked section illustrating a bright spot with a top sand pick in green. (b) Time-window crossplot generated from a 40-ms window around the top-sand pick.

Although random noise appears to be the principal component of noise on AVO crossplots, other types of noise can have an influence on the observed trends (such as RNMO).

Porosity and shale content. A change in lithology can be modeled by varying the porosity of the sand or the shale content. Increasing the porosity has two effects—to decrease the AVO gradient (i.e., the Poisson ratio contrast with the overlying shale has been reduced) and to decrease the intercept (owing to a decrease in the impedance contrast). The decrease in intercept gives rise to a low-angle porosity trend that intercepts the gradient axis.

Changing the porosity of the sand in the model (but still maintaining the criteria of noninterfering reflections) results in a crossplot that shows a series of ellipses aligned at an angle to the gradient axis (Figure 2c). The trend imposed by the eye on this data cluster would be somewhere between the porosity trend and the noise trend.

A change in lithology due to increasing shale content of the sand also lowers the gradient and intercept, but the trend is steeper than the porosity trend. It may even be close to the noise trend. In the case where the shale component in the sand is different from the overlying shale (as might be found at a sequence boundary), then the "lithologic trend" would have a nonzero intercept value.

This discussion illustrates that a given area might not have one background trend but a possible variation, depending on the relative contributions of shale and porosity which, in turn, are determined by

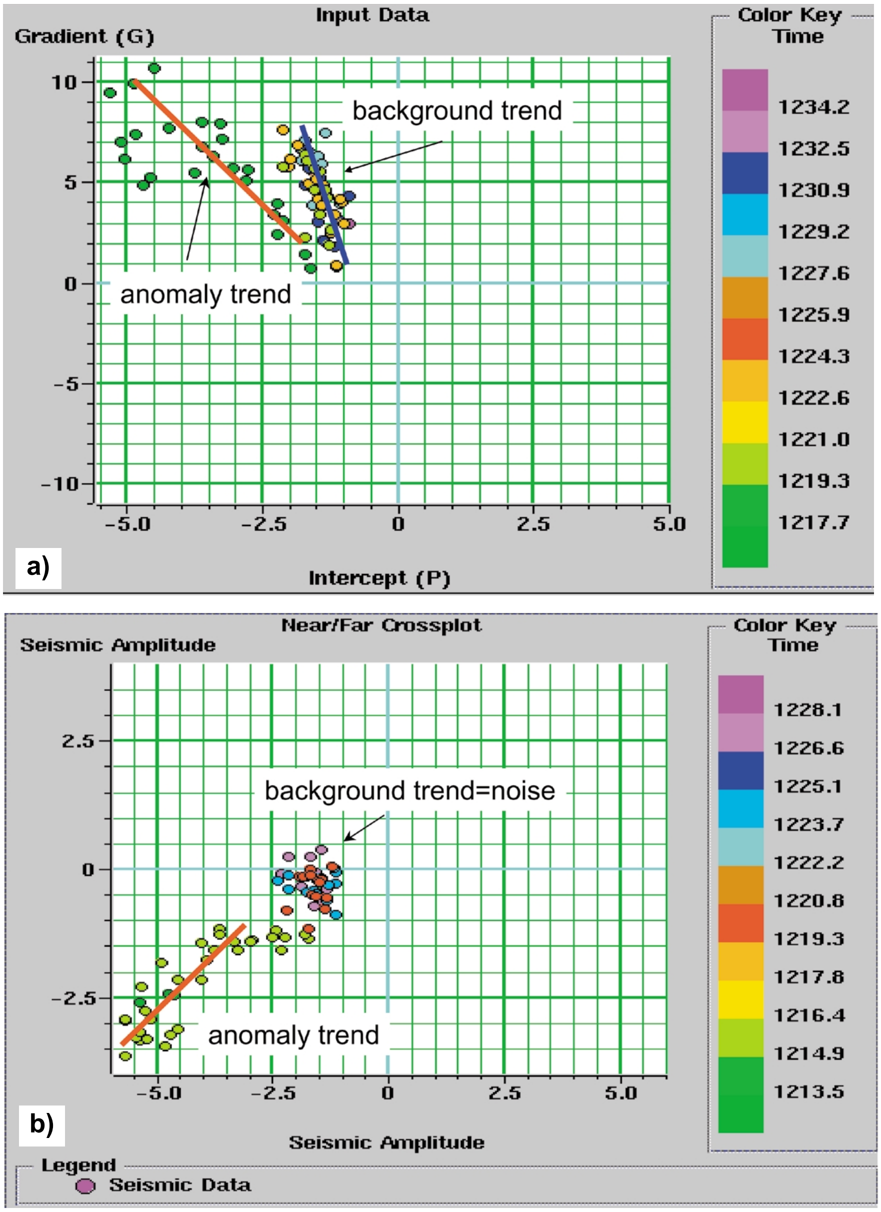

Figure 4. Horizon crossplots. (a) R0/G crossplot for the pick shown in Figure 3 and illustrating the different trends associated with the bright spot and the "background" reflectivity. (b) Near/Far crossplot illustrating that the background trend on the R0/G crossplot is related to noise and not to lithology.

sedimentary facies. This is a moot point, however, given that in practice noise obscures the lithologic trend.

The gas effect. Figure 2d shows the effect of fluid substituting the sands of varying porosity (again the reflections are separate and noninterfering). The effect of the hydrocarbon is not so much to define a trend as to create a separate data cluster occupying a position to the left of the brine-bearing data points. The greater the effect of the hydrocarbon on the V_P/V_S ratio of the sand, the further the data points will plot away from the brine-filled data points.

In these models, the optimum discriminator can be determined statistically (Figure 2e). This will depend on the amount of noise, the lithologic variation, and the magnitude of the gas effect. This trend may or may not pass through the zero point. In the real-world case, knowledge of the noise trend could be used to model the optimum discriminator (assuming all other effects on R0 and G could be accounted for). If the lithologic variation is not large, a range of trends may exist that would discriminate equally well.

Time-window crossplots. So far, discussion has centered on the horizon crossplot. If samples from a time window are incorporated into the crossplot, the horizon sample points, together with reflections from the base of the sand (plotting in the upper left quadrant), are included in an ellipse of points centered on the origin (Figure 2f). The organization of data around the origin does not have a physical significance; it is simply the result of the fact that the mean of seismic data is zero. Noise related to sampling parts of the waveforms other than the maxima is infilling the area between the two data clusters.

Cambois has shown that the slope of what might be called the "time-window" trend (i.e., a line drawn through the data which passes through the origin) is dependent on the S/N of the data. The lower the S/N, the steeper the trend. This trend may be close to the optimum discriminator or it may not. The noisier the data, the closer this time-window trend will be to the noise trend.

In the case where S/N is very high, it could be argued that the line derived from a time-windowed crossplot is equivalent to an average rock property trend (call it the fluid line if you must) that can be inferred from a crossplot derived from well data. Given the general level of S/N of most seismic data, this occurrence is likely to be rare.

Crossplots in practice. It is clear that the authors see little value in time-window crossplots, owing to the effects of noise. However, these crossplots have successfully recognized hydrocarbon-related AVO anomalies, usually related to gas where the change in crossplot position is dramatic. Oil-related anomalies are usually well hidden in the noise of the plot. Figure 3 shows an example of a time-window crossplot related to a bright spot and its correlative reflector. The samples from the bright spot are clearly anomalous in terms of their AVO behavior.

On the other hand, the horizon crossplot clearly targets the reservoir of interest and helps determine the noise trend while revealing the more subtle AVO responses. Figure 4 shows the horizon crossplot for the portion of reflector marked in Figure 3. The responses are characterized by negative reflections and positive gradients (i.e., a class IV response). The nonbright part of the reflector has a high angle slope shown on the near/far crossplot to be almost totally due to noise. The bright spot has a lower-angled slope on the crossplot (owing to higher S/N), and it is possible to see the noise trend as a second-order effect.

Horizon crossplots can be generated from maps created from AVO attributes or partial stack 3-D interpretations. These crossplots need to be made in a number of locations to make sure that an adequate sample has been analyzed. In practice it may not be easy to identify an optimum discriminator from the crossplots, but the noise trend is usually straightforward to determine.

AVO anomaly maps can be created from linear combinations of R0 and G. These combinations are usually of the form R0+Gx, where x=-G/R0 and is determined from the slope of the trend on the crossplot. Considering that the reflection amplitude is described by $Rc=R0+G\sin^2\theta$, x represents an "effective" angle. Any slope on an AVO crossplot is an "effective angle stack." However, which trend should be used to create the AVO anomaly map?

The answer (as in many issues in seismic interpretation) is that it is impossible to be definitive. Although crossplots are useful to determine which equivalent stack is likely to be most discriminatory in terms of fluids, they are only a one-dimensional view of a limited amount of seismic data. The real interpretation issue is whether the anomalous responses represent porosity or hydrocarbon effects, and the only way to determine which interpretation to make is to analyze the relationship of the anomaly to mapped structure. In some cases, the equivalent angle stacks representing the noise trend, the time-window trend, and the optimum discriminator may give similar results, owing to the fact that the hydrocarbon effect is a displacement at a high angle to all these trends.

Probably the best approach to the use of crossplots in interpretation is to be published by Hendrickson (in press). He illustrates the use of a range of equivalent angle stacks in an interpretation, examining the amplitude conformance to structure on each stack as well as recognizing their significance in terms of the AVO crossplot. Interpretation is a question of "covering all the angles" so to speak.

Suggestions for further reading. "AVO attributes and noise: pitfalls of crossplotting" by Cambois (SEG 1998 *Expanded Abstracts*). "Framework for AVO gradient and intercept interpretation" by Castagna et al. (GEOPHYSICS, 1998). "Principles of AVO crossplotting" Castagna and Swan (*TLE*, 1997). "Another perspective on AVO crossplotting" by Foster et al. (*TLE*, 1997). "Stacked" by Hendrickson, (*Geophysical Prospecting*, 1999). "Yet another perspective on AVO crossplotting" by Sams (*TLE*, 1998).

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