AVO analysis demystified

Amplitude variation with offset interpretation doesn't have to be a black box.

AUTHORS

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Even before S.R. Rutherford and R.H. Williams proposed their three-fold classification of amplitude variation offset (AVO) types in 1989, the geophysical community has sought to extract value from the information contained in the unstacked seismic gathers. A large number of schemes for organizing, simplifying or portraying information extracted from the gathers has been proposed. And, while a lot of these have merit, one of the unintended consequences is that a lot of people think of the subject as fundamentally arcane and impenetrable. Nothing could be further from the truth.

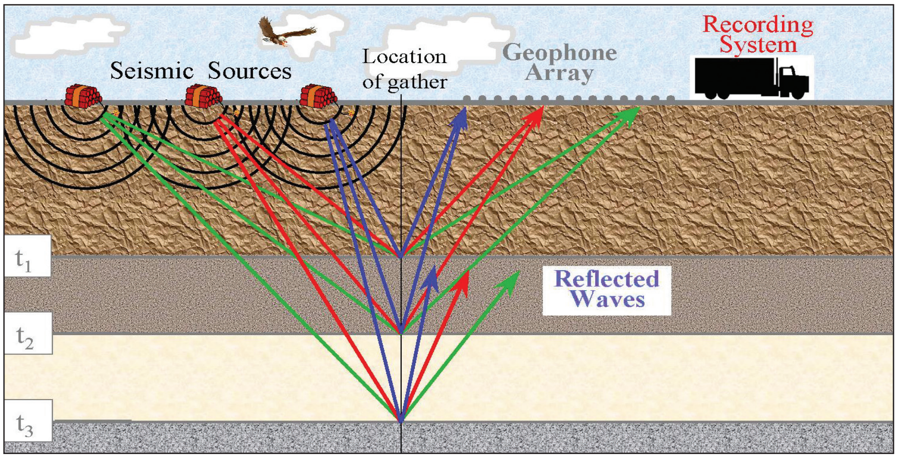

Figure 1. This diagram shows how the angular relationship varies from trace to trace in a common midpoint seismic gather. Each set of colored lines represents the ray paths of some of the energy contributing to an individual trace in the seismic gather. (All images courtesy of e-Seis)

Basic background

Modern seismic data are acquired in such a way that each point in the subsurface is sampled multiple times during each survey. Each sample comes from a different combination of seismic sources (shots) and geophones and, therefore, each sample will have a different angular relationship between the shot, the sample location and the geophone (see Figure 1). As the geophones are moved and different shots are set off, a vast library of data is developed.

A number of procedures are applied during routine processing of the data to ensure that the spatial (and temporal) coordinates of each sample are known as well as possible. The result of this processing is that a catalog of information is assembled for each X-Y location in the survey. Each catalog is known as a common-midpoint gather (gather) and is comprised of traces. Each trace represents the reflected energy from the series of all time samples beneath the X-Y location of that gather; different traces in the gather result from different angular relationships between shots and geophones (see Figure 1 and the left panel of Figure 2).

These traces, in each gather, contain a large amount of useful information which may be made available to the geophysical interpreter as he seeks to broaden his understanding of the subsurface through seismic. Unfortunately, there's no good way to visualize and map this information in its raw form. It has to be reduced to something manageable.

AVO analysis

Reducing the information into something useful is a two-step process. First, the interpreter must decide what information he or she wants to extract. Then, a display decision must be made. In the case of the stack, the extracted information is the average amplitude for each time sample of all of the traces in the gather (see Figure 2 for a graphic representation of this). It is displayed either as a wiggle or with some color code designed to reveal the magnitude and direction of the average amplitude. The big advantage of the stack is that, while all of the AVO information is lost, a lot of the random errors associated with each individual sample are eliminated, resulting in a very robust and stable look at the reflectivity of the subsurface.

AVO analysis is not very much more complicated than stacking the data. Figure 2 shows a set of traces in a gather. These traces have been selected so that they all are representative of a line of observations extending vertically from a particular point on the surface to some pre-selected depth (in two-way, acoustic travel time). They have been adjusted so that corresponding samples on different traces reference the same two-way travel time. They are arranged in order with the trace coming from the shot-receiver pair closest to the gather lying on the left. Remember that all of the traces in a gather have the same X-Y location.

Also shown on Figure 2 is a graph. This graph plots the value of the amplitude for each trace at time t^2 on the ordinate (or Y-axis) against $\sin^2\Theta$ on the abscissa (or X-axis), where Θ is the angle between the shot (or receiver) and the line of the trace. Higher angles obviously are associated with farther offsets. For reasons that are discussed elsewhere, $\sin^2\Theta$ ransforms the relationship between amplitude and offset into a more-linear one. Because the relationship, as graphed, is nearly linear, a simple, least-squares, best-fit line can be used to describe the distribution of the amplitudes (shown on Figure 2 as a gray line going through the data points). This line can be completely and uniquely characterized by two parameters: the value where it intersects the ordinate (called "P"), and its slope (called "G"). To the extent that the line fully describes the distribution of the amplitudes, these two parameters (P and G) fully describe the line and, therefore, the amplitude variation with offset (AVO).

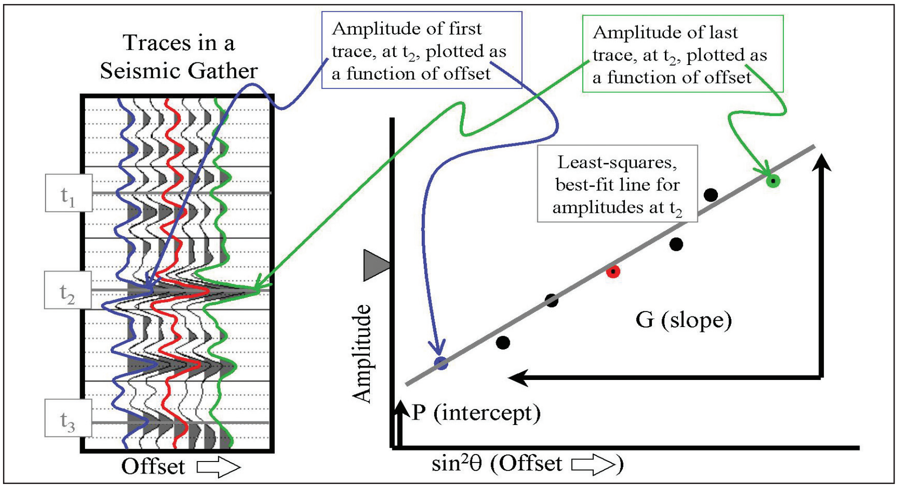

Figure 2. A basic AVO analysis after appropriate geometric corrections the individual traces for one gather are displayed in the panel on the left; the colors correspond to the colors in Figure 1. A graph may be constructed at any point in time (e.g. t_1, t_2 or t_3) to analyze the amplitude variation with offset of the traces at that time; the graph at the right shows one such plot for time t_2. The gray line is a least-squares, best-fit to the natural distribution; values for P and G are extracted from analysis of the best-fit line. Triangle shows the average amplitude of all of the traces at t_2.

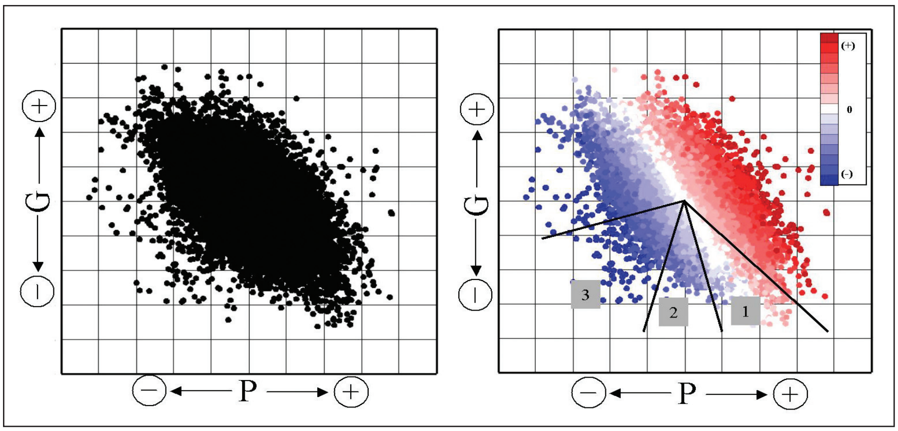

Figure 3. On the left, a cross-plot shows P versus G for every time sample for every gather in a volume of seismic data. The data have been normalized to constrain P and G to the same range of values. On the right, the same cross-plot has been color-coded to show the stacked amplitude of each point; light to dark blues are low to high amplitude troughs, and pink to dark reds are low to high amplitude peaks. The three regions denoted 1, 2 and 3 are defined by the three AVO classes of Rutherford and Williams.

The terms P and G often go by other names. The value of P is defined where there is no offset; hence, P is often referred to as the "zero-offset" amplitude. A zero-offset would, hypothetically, occur where the shot and receiver were at the same place and the energy went straight down and came straight back, yielding another name for P: the "Normal Incident" amplitude. In addition to "Slope," G is often referred to as the "Gradient" or the "AVO Gradient."

There are other pieces of information or AVO parameters which may be extracted from the traces or from the graph of their amplitudes. Sometimes a subset of the traces such as those reflected through a small angle (or from a short offset distance) are stacked independently of the others and, in this case, referred to as "Nears." Other groupings, such as those reflected through a large angle or an intermediate angle, are called "Fars" or "Mids."

This is all of the information one is likely to see extracted from an "AVO Analysis." There are other, more esoteric values sometimes extracted. For example, the $\sin^2$ transformation does not make the relationship strictly linear; another term is required, and it has petrophysical significance. The problem is that real data are almost invariably too noisy for that extra term to have any real value. So, practically speaking, we have the following AVO parameters from which to make our interpretations: the Ps and Gs, which together completely define the gathers; the stack, which averages all of the information from the gathers; and the nears, mids and fars, which average subsets of the information in the gathers.

Displaying AVO information

This is where the geophysical community has gotten really very inventive. As we've seen, the Ps and Gs effectively contain all of the information from the gathers. It's instructive, therefore, to start with the Ps and Gs and then see how other products relate to them.

Figure 3 is a plot of all of the values of P and of G from a seismic dataset, cross-plotted against each other; we refer to this plot as representing AVO space. The left-hand panel of Figure 3 is obviously of little value; it shows that there is some regularity to the data, but little more. The right-hand panel of Figure 3 shows the same data color-coded to highlight the amplitudes of the stacked dataset. The distribution of the colors should come as no surprise: A negative amplitude is a trough and a bunch of trace amplitudes distributed so as to yield a strongly negative P with a strongly negative gradient (G) that will have the highest average negative amplitudes (large, dark-blue troughs on the stack). Superimposed on the right-hand panel are the three regions defined by Rutherford and Williams' AVO classes. Clearly there's something interesting going on here, but it's not well-defined by either the stack or the classes. The stack shows a fairly discriminating pattern of amplitudes between the classes, but the same range is present outside the classes. And the classes fail to cover more than a small portion of the possible combinations.

Applying the same approach of looking at a single parameter from the AVO analysis within AVO space to the Ps, Gs, nears and fars yields a similar conclusion. As shown in Figure 4, any single parameter fails to show

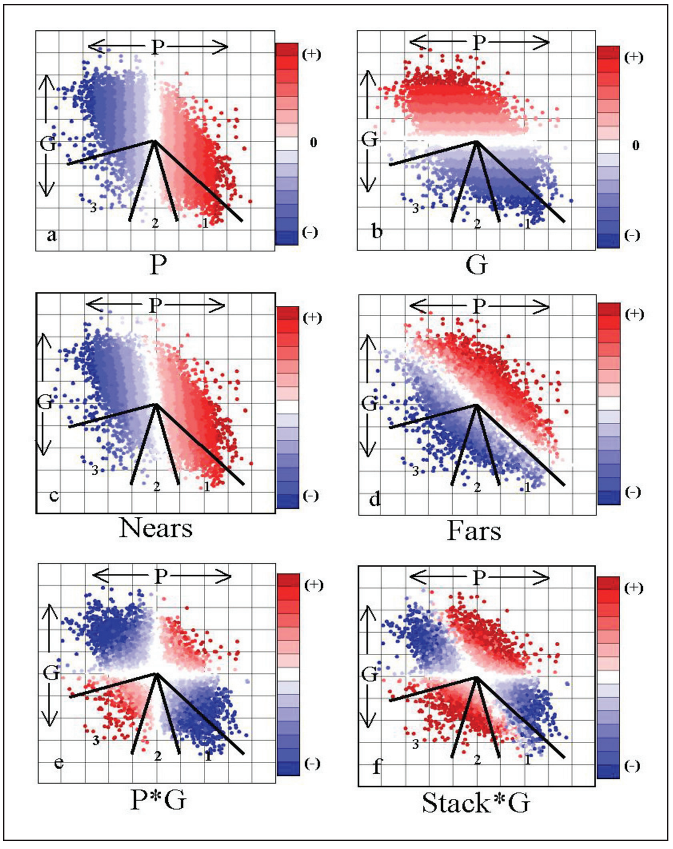

Figure 4. These cross-plots show the distribution of AVO parameters in AVO space. The datasets and cross-plotting parameters are identical to those in Figure 3. In panels a and b, the parameters P and G (which completely define the linear aspects of AVO space) appear as uniformly varying, one-dimensional gradients across AVO space. In panels c and d, the nears and fars show similar one-dimensional gradients, inclined at angles intermediate between those shown by P and G. In panels e and f, two of the AVO parameters are combined and the resulting attribute is displayed in color. In panels a, c and e there is good discrimination by the value of the AVO parameter (or combination) between the classes of Rutherford and Williams but, as with the stack, there is the same range in values outside the classes.

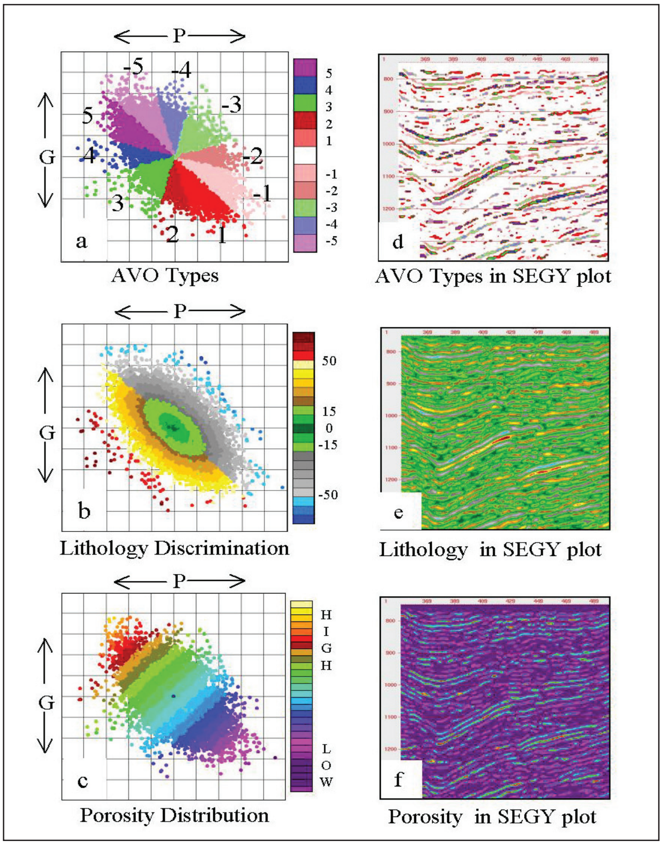

Figure 5. Using the same datasets as Figures 3 and 4, the AVO space has been subdivided into more rational and useful domains. In 5a the entire space has been divided into AVO classes by extending the original classifications around the entire unit circle. In 5b the same space has been divided into domains that are reflective of lithologic variations: The shale background (shades of green) is close to the origin; non-shale rocks, which are softer than shales, are yellows and browns (reds and maroons are extreme departures, which may be indicative of compressible fluids); relatively hard non-shale rocks are shades gray and blue. In 5c the entire data set is divided, yet again, to reflect variations in porosity — low-porosity rocks are observed to fall in the southeast part of the plot and higher porosities fall to the northwest. Panels d, e and f show seismic sections prepared using the domain divisions illustrated by panels a, b and c.

much of the information that's inherent in the data. Schemes to combine two of the parameters by multiplying them only make things worse (see Figure 4, also).

There are techniques, however, which can capture a lot of the richness of AVO space and put it in a form that is useful to an interpreter. One such approach is illustrated in Figure 5. A couple of underlying assumptions and observations are necessary. The first is that changes in lithology, porosity and fluids affect where points plot in AVO space. The second is that the background lithologic trend is shale and that shale-to-nonshale contrasts will plot away from the background.

When AVO space is divided using this simple approach, everything begins to make sense. The power of the Rutherford and Williams approach is now distributed over the entire AVO space. The richness of the information in the gathers is captured and divided into geologically meaningful domains.

In the approach that is illustrated in Figure 5a, AVO space is divided into 10 AVO types. An alternate division of the AVO space (Figure 5b) yields information that is sensible from a gross lithology perspective. The assumptions, in this case, are simple: The background trend is shale, and deviations from the background trend are shale to nonshale contacts. Finally, it can be seen that there is generally a regular distribution of porosity within AVO space; this distribution is shown in Figure 5c.

There's no black box in any of this, just useful information derived from AVO analysis and displayed in a familiar and intelligible format. The interpreter can now look at sections in terms that are useful and intuitive.

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