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Conforming and Non-conforming Sands – An Organizing Framework for Seismic Rock Properties

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Abstract

A new classification for AVO (amplitude versus offset) has been proposed to include all possible combinations of near and far trace polarities and amplitudes. This classification admits all sands regardless of the sign of the impedance contrast of the sand with the overlying shale or the direction (positive or negative) of change in impedance contrast reflectivity with increasing offset.

Previous AVO classifications have assigned gas sands to various classes (one through three, four, or five – depending on the author). These classes cover only a subset of the possible combinations of reflectivity that can occur with offset. Generally, the tops of sands in these classes are characterized by negative reflection coefficients or by positive reflection coefficients, which become negative with increasing offset. In the new classification these sand classes are defined as conforming types, whereas sands with positive reflection coefficients on both near and far offsets or those, which have negative reflection coefficients becoming more positive with increasing offset, are described as non-conforming types.

By providing a complete classification of AVO types a solid framework is established for systematically investigating rock and fluid properties, of each of the resulting ten AVO types, with seismic data. An understanding of the characteristics of the two categories of sand types and the variations of AVO response for the different sands within the categories is critical in accurately assessing any geologically-interesting property.

Introduction

Last year a new classification for AVO responses was proposed (Young and LoPiccolo, 2003). This classification covers all possible AVO responses and is independent of the fluid content of the beds. It includes and expands upon the previous AVO classifications.

In 1989 Rutherford and Williams introduced a three-fold classification of AVO (amplitude versus offset) characteristics for seismic reflections from the interface between shales and underlying gas sands. The classification scheme they proposed is explicitly defined for gas sands and has become the industry standard; it has proven its validity and usefulness in countless exploration efforts.

In 1997 Castagna and Swan proposed AVO crossplotting wherein an estimate of the normal-incidence reflectivity is plotted against a measure of the offset dependent reflectivity. Using this approach Castagna and Swan graphically illustrated the continuum between the classes and defined the characteristics of the classes using what they termed AVO Intercept and AVO Gradient. They also added a class 4.

In the 2003 paper Young & LoPiccolo expanded and partly redefined the currently used classifications. In order to distinguish among the schemes the term "types," as opposed to "classes," was proposed to name the different categories. In order to preserve congruity, where the schemes overlapped, the sands, which Rutherford and Williams would call class 1, 2, or 3, were renamed as types 1, 2, or 3. Type 4 of the new classification includes parts of the domains, which Castagna and Swan assigned to their class 4 and their class 3. A type 5 replaces part of Castagna and Swan's class 4, and types –1 through –5 are added which complete the spectrum. The new classification provides an unambiguous way of sorting the entire range of combinations of normal-incidence reflectivity and offset-dependent reflectivity, irrespective of the cause or the direction of change of the offset-dependent amplitude variations.

It is further suggested that AVO effects are best described as being not just between shales and underlying sands, but between non-shale lithologies and the overlying rock (whether it be shale or not). Because non-shale lithology is rather an awkward term the name “sand” will be used in the following discussion, but the reader is asked to bear in mind that a larger and not especially accurate definition of sand is implied. Clearly, the classification goes beyond gas sands in its intended application. Variation in AVO should be considered a physical phenomenon, the root cause of which requires interpretation.

AVO Types Classification

The new classification was predicated on an analysis of the gradient of the change in amplitude with increasing offset and the value of the intercept of that gradient with the zero-offset or normal-incidence trace. Implicit in the new classification is a tightening of the usage of the term AVO to a more literal definition: anaBy making the amplitude variation with offset part of the definition of AVO types, a broader spectrum of combinations presents itself. Reflections may be either positive, negative, or zero and may either increase, decrease, or remain the same with increasing offset.

The authors endorsed Castagna and Swan’s AVO crossplotting approach and reproduced their plot, with minor modification, to illustrate the proposed classification (see Figure 1). The ordinate is designated G, defined by fitting a linear approximation to the slope of the amplitude variation with offset and the abscissa is P, defined as the value of the linear approximation at the intercept, where the offset is zero. In the illustrated construction P and G are both dimensionless and scaled to the same dynamic range. This implies, of course, that how the individual data points fall in the construction of the cross plots may be partly a function of the size and location of the sample taken from the seismic data; there is the possibility that the AVO type assigned to a given reflection may change as a function of the size and location of the sample within which it is included. This is a shortcoming inherent in any AVO classification using this crossplotting approach; it is not unique to the current proposal.

The proposed division boundaries radiate from the origin with a fixed angular relationship (see Figure 1). This basis for divisions has the benefit of being very straightforward to calculate; it also preserves relationships as the sands thin.

The obvious, initial divisions correspond to the four quadrants of the unit circle: P and G are individually either positive or negative and the domains are unique as a function of the combination of these attributes. Four more domains present themselves at and near the boundaries between the quadrants where either P or G will vary little or not at all. A further division results from the following consideration. If one assumes that the ratio of the P-wave velocity to S-wave velocity in non-hydrocarbon-bearing zones is constant at (approximately) 2 and that the density contrast across reflecting horizons is negligible (as discussed by Foster, Keys, and Reilly, 1997) then the division between positive (1 through 5) and negative (-1 through –5) AVO types corresponds to the linear fluid line of Foster (et al, 1997). As illustrated in Figure 1 sands which fall to the southwest of that line (positive AVO types in the present paper) are described as “conforming sands” in that the effects of decreasing shaliness and increasing gas content are similar: sands are displaced to the southwest by either of these phenomena. In “non-conforming sands” there may be no discernible gas effect, if there is a gas effect it is unchanged from the conforming sands, it tends to displace points to the southwest; the shale effect is the opposite and decreasing shaliness tends to displace points to the northeast.lysis of *variations* in amplitude versus offset.

Table 1 describes the ten AVO types included in the proposed classification. The AVO types are also illustrated graphically in Figure 2, which shows the general relationships between the amplitude and offset for all of the types.

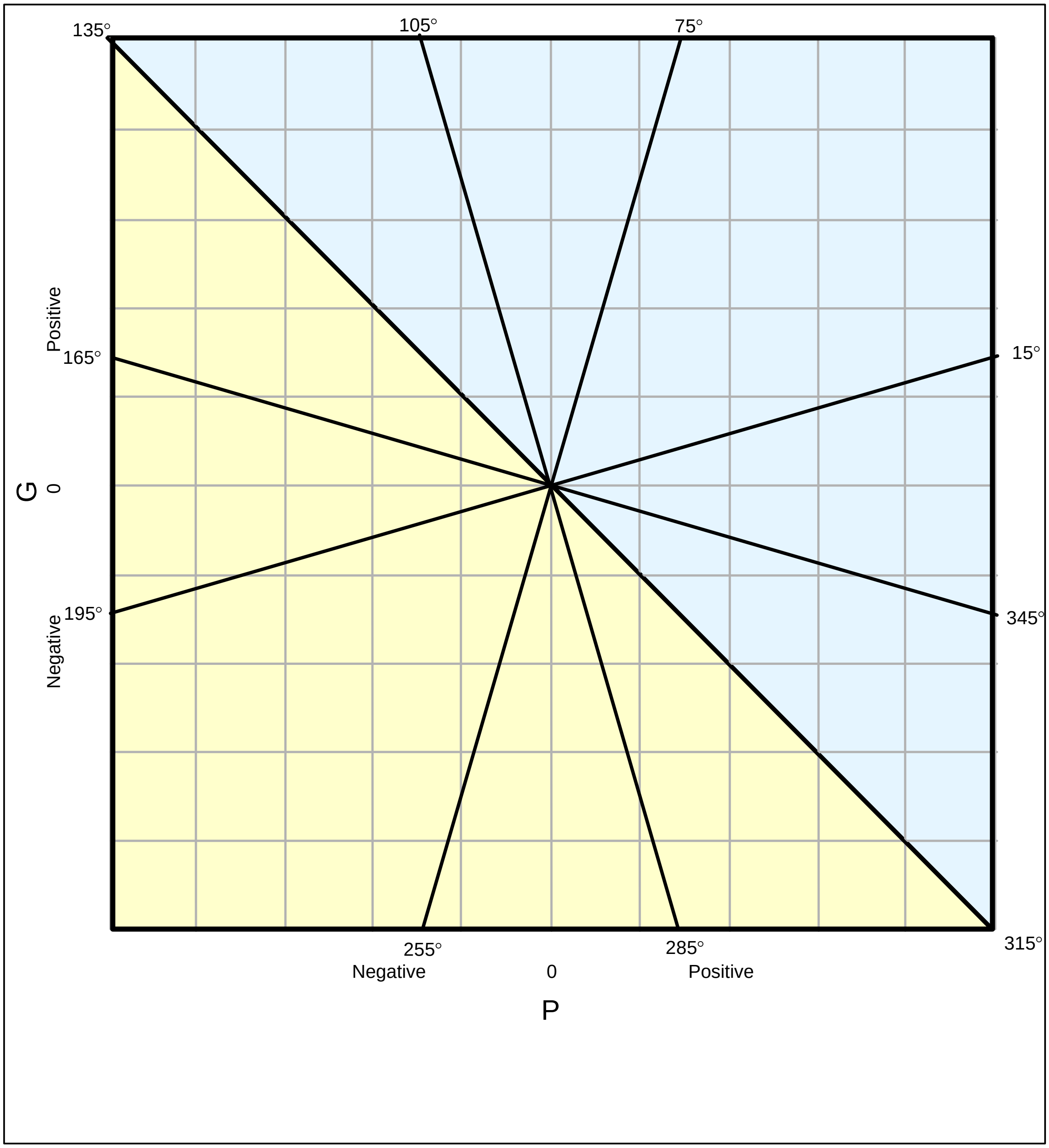

Figure 1. Proposed classification of AVO types as a function of P and G. P and G are both dimensionless and are scaled to have the same range of values.

Table 1 AVO Types Characteristics

	AVO Type	P (intercept)	G (gradient)	Amplitude vs. Offset
Conforming Sands	1	Positive	Negative	Peak decreasing in amplitude with offset; becomes a trough in the fars
	2	Near zero	Negative	Nearly transparent becoming trough; amplitude increases with offset
	3	Negative	Negative	Trough increasing in amplitude with offset
	4	Negative	Flat	Trough changing little in amplitude with offset
	5	Negative	Positive	Trough decreasing in amplitude with offset
Non-Conforming Sands	-1	Positive	Negative	Peak decreasing in amplitude with offset
	-2	Positive	Flat	Peak changing little in amplitude with offset
	-3	Positive	Positive	Peak increasing in amplitude with offset
	-4	Near zero	Positive	Nearly transparent becoming peak; amplitude increases with offset
	-5	Negative	Positive	Trough decreasing in amplitude with offset; becomes a peak in the fars

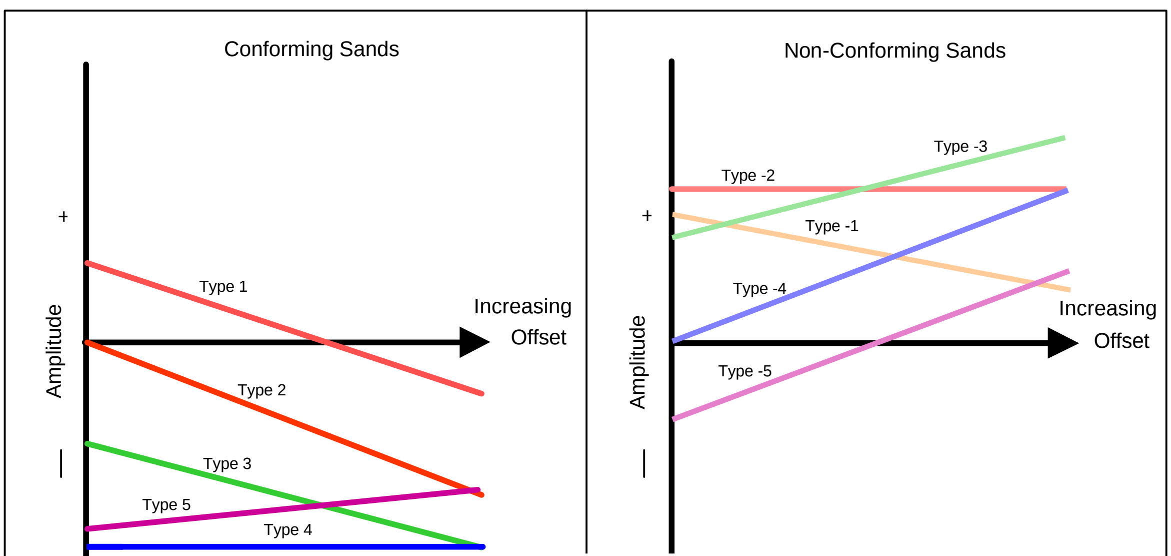

Figure 2. General relationships between the amplitude of the reflection at normal incidence and the amplitude of the reflections with increasing offset for the different AVO types.

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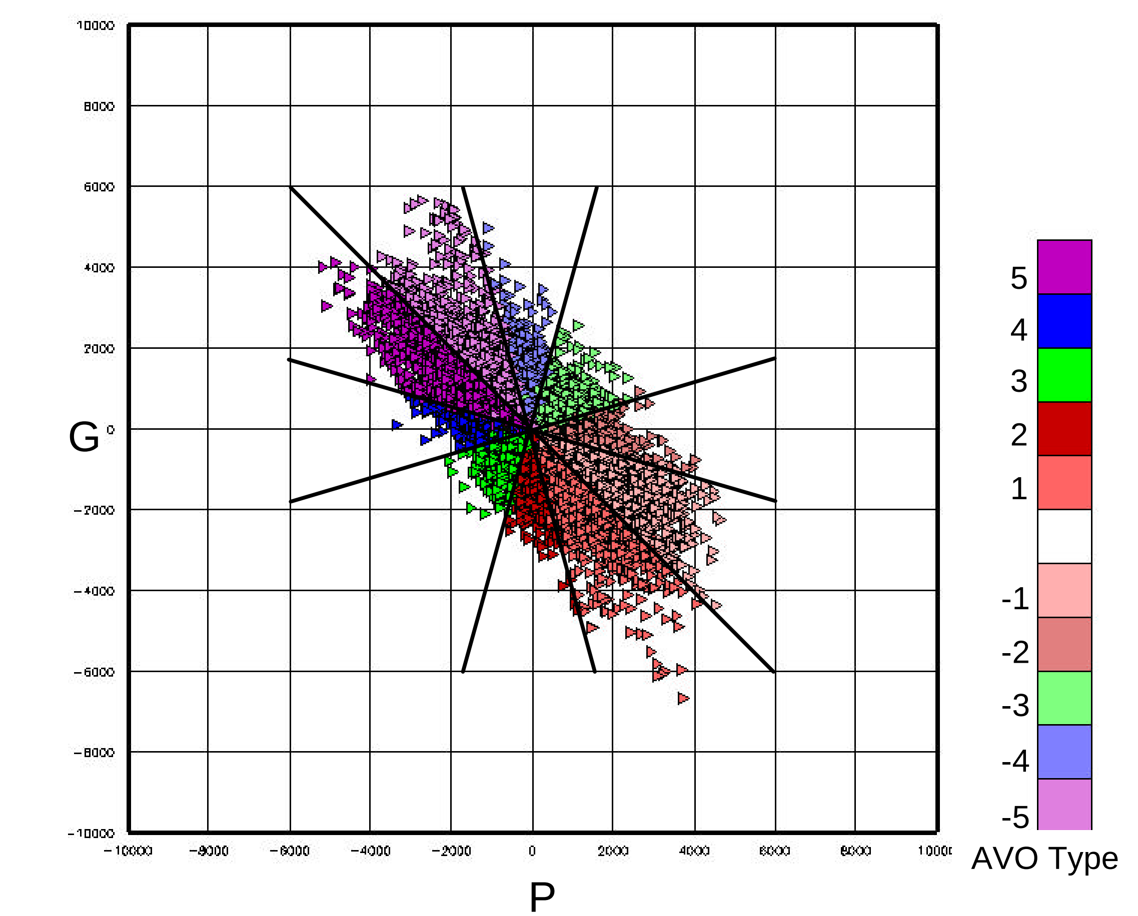

Figure 3. Scatter plot showing distribution of real data set evaluated using the proposed classification scheme. Each sample in the siesmic data set is evaluated for P and G; the whole set of P's and G's is scaled; and, the points are plotted accordingly. Color codes are assigned according to the divisions laid out in Figure 1 (and reproduced by the diagonal black lines here). The color-coded points may then be output using an appropriate SEGY format and displayed as record sections

In order to calculate AVO types for classification using the proposed scheme we apply the following procedure. An appropriately trimmed, muted, moved-out, and migrated set of gathers is analyzed on a sample-by-sample basis. A least-squares, best-fit line is fitted to the amplitudes. The slope of the line gives G and the intercept of the line, when projected back to the ordinate, gives P. The values of P and G are used to calculate a position on the unit circle and the AVO type is found in a look-up table. An example of the results of this type of calculation is illustrated in Figure 3 by crossplotting color-coded values of P and G. Finally, a lithology template is created and the shale (or shaley lithologies) are masked out. Thus, in effect, AVO type becomes an instantaneous attribute of the seismic data. The association with non-shale lithologies is important and is kept in the classification because these rocks provide most of the reservoirs of interest.

The salient differences between this scheme and the earlier ones are as follows:

- Sands (non-shale lithologies) are designated to be conforming or non-conforming.
- The field of conforming sands is re-divided to include a fifth type.
- The AVO types are defined using an angular division of a unit circle inscribed in the field of P's and G's.

- AVO type is a continuously distributed property of the seismic data.

The proposed classification permits the easy calculation of the AVO types, which can then be presented in SEGY format. By combining this information with knowledge of the geology of the area, attractive exploration targets can be more easily and accurately identified. Modeling studies suggest that all ten AVO types of sands (non-shale lithologies) should exist.

AVO Types and Seismic Rock Properties

The previous discussion simply points out that a shale over a non-shale interface can result in any combination of P and G. All possibilities are broken into ten AVO types. While an interface resulting in any of the ten types can exist at any depth or geologic environment there are some strong tendencies that make a volume of AVO types very powerful. For example, when exploring in an environment where type 1's and 2's are expected, the presence of a type 5 should result in a closer evaluation as to its cause.

AVO types are the result of the contrast of the rock properties of the overlying shale to the non-shale being investigated. Because different geologic environments tend to favor different types of contrasts the resulting AVO types also have regular tendancies. For example, in shallow, young rocks the sands tend to be lower in impedence than the shales and the resulting AVO type values tend toward the higher numbers (3's, 4's and 5's). With depth the the sands generally become faster than the shales and the AVO types will decrease to 1's and 2's. Similarly, the expected AVO types in geopressure are 1's and 2's. Of course, AVO types 3 and 4 may be found in deeper overpressured sections, but when they are a critical geologic assessment should be performed to vet them and accurately assign risk.

AVO typing is also controlled by lithology. Sands that display a low ratio of compressional velocity to shear velocity will tend to be conforming AVO types. This type of sand is generally non-cemented or lightly-cemented, but still granular in nature. If the sands are well-cemented or if a carbonate is encountered the AVO type will generally be negative (non-conforming).

Coals will almost always show a much slower compressional velocity than either sands or shales; as a result, coals tend to be types 4 and 5.The presence of compressible fluids, especially gas, has the effect of lowering the impedance; the effect is emphasized with offset. Thus P and G

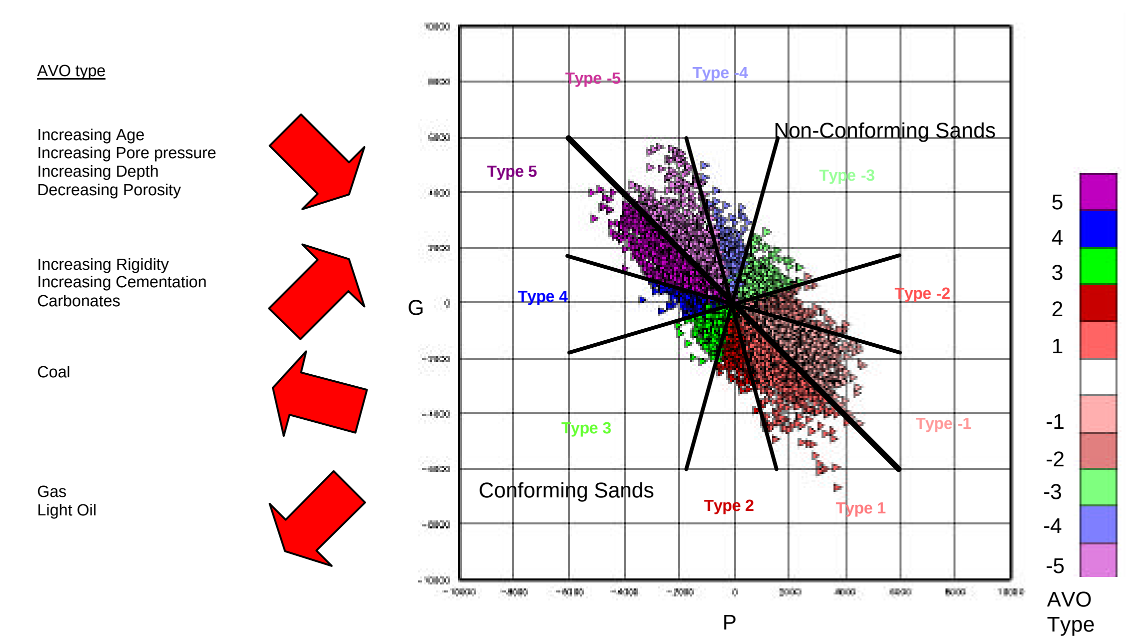

Figure 4. Bold red arrows show the direction of the effect various lithlogic and geologic variations have on AVO type.

are both shifted in a negative direction with the addition of compressilbe fluids. Gas and light oil tend to cause the AVO type to be positive; a shift of the AVO type from negative to positive can itself be a DHI, although when the sand is very well-cemented the effect may be slight. Also a wet, type 2 AVO sand may show a transition updip into a type 3 AVO with the addition of gas.

Figure 4 summarizes the previous discussion, graphically.

Summary

An AVO classification has been published wherein all possible combinations of normal-incidence reflectivity and offset-dependent reflectivity, for all seismic energy coming from the top of non-shale lithologies, are subdivided into ten types. Broadly, the divisions result from dividing a unit circle into eight domains depending on the attributes of P and G: they each may be positive, near zero, or negative, independently of the other. Two of the domains are further subdivided and all of the domains are grouped by a further distinction as to whether the types are: conforming, where decreasing shaliness and increasing gas have similar effects; or, non-conforming, where decreasing shaliness and increasing gas have opposite effects (or gas has no effect). The definitions are divorced from a gas-sand association and applied, without discrimination, to any non-shale lithology. This approach also departs from conventional AVO analyses in that the AVO attribute becomes a continuously distributed attribute of the seismic data.

We are in the early stages of fleshing out the implications of all of the different AVO types, but some interesting relationships are already becoming apparent. The implications of these relationships to hydrocarbon exploration is profound. By combining a knowledge of the local and regional geology with an analysis of the AVO types an entire volume of seismic data may be sorted into events which may be reasonably associated with hydrocarbons and those which are probably not.

References cited

Castagna, J.P. and Swan, H.W., 1997, Principles of AVO crossplotting: The Leading Edge, v.16, no. 04, p. 337-342

Foster, D.J., Keys, R.G. and Reilly, J.M., 1997, Another perspective on AVO complotting: The Leading Edge, v.16, no. 09, p. 1233-1237

Rutherford, S.R. and Williams, R.H., 1989, Amplitude-versus-offset variations in gas sands: Geophysics, v. 54, no. 06, p. 680-688

Young, R.A. and LoPiccolo, R.D., 2003, A comprehensive AVO classification: The Leading Edge, v. 22, no. 10, p. 1030-1037