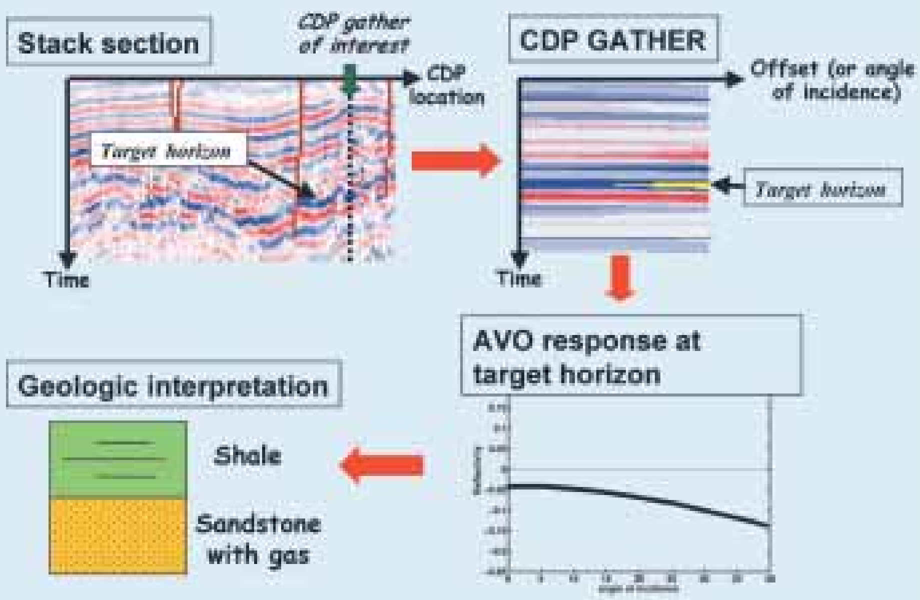
AVO responses: The good, the bad and the evil

AVO analysis provides the geologists with a powerful tool that give information about pore fluids, lithologies and reservoir pressures. However, AVO signatures can easily be misinterpreted without a proper feasibility study.



The basic principles of AVO analysis. The seismic stack section gives good information about stratigraphy and depositional geometries. However, important information about fluids and lithologies is hidden in the pre-stack seismic gathers. The AVO analysis seeks to extract this "hidden" information about rock and fluid properties.

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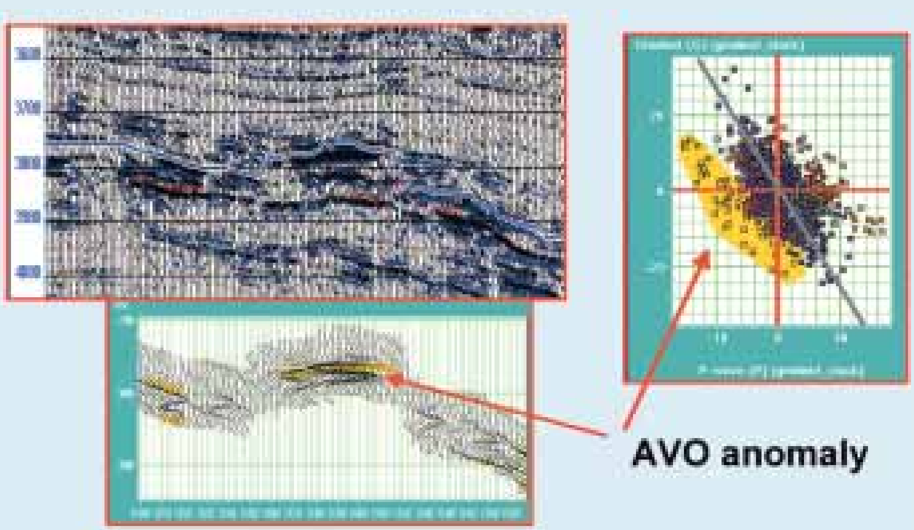
More than 20 years ago, William Ostrander, winner of the Virgil Kauffman Gold Medal of the Society of Exploration Geophysicists, published a break-through paper in the scientific journal *Geophysics*. He showed that gas saturated sands capped by shales would cause an **a**mplitude **v**ariation with **o**ffset (AVO effect) in pre-stack seismic data. Shortly after, AVO technology became a commercial tool for the oil industry.

A revival

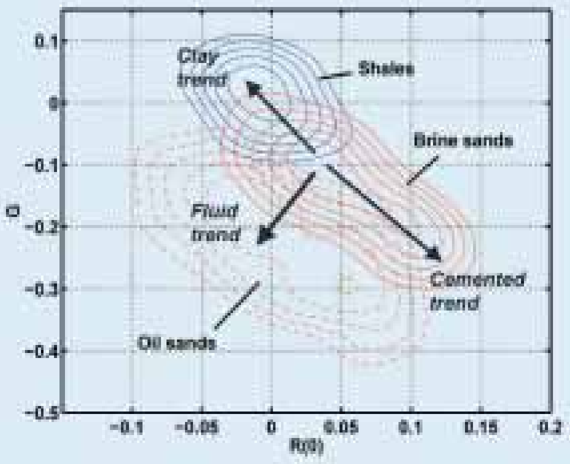
The AVO technique soon became very popular, as it was now possible to explain seismic amplitudes in terms of rock properties. The technique proved successful for hydrocarbon prediction in many areas of the world, but in other cases it failed. The technique suffered from ambiguities caused by lithological effects, tuning effects and overburden effects. It turned out that



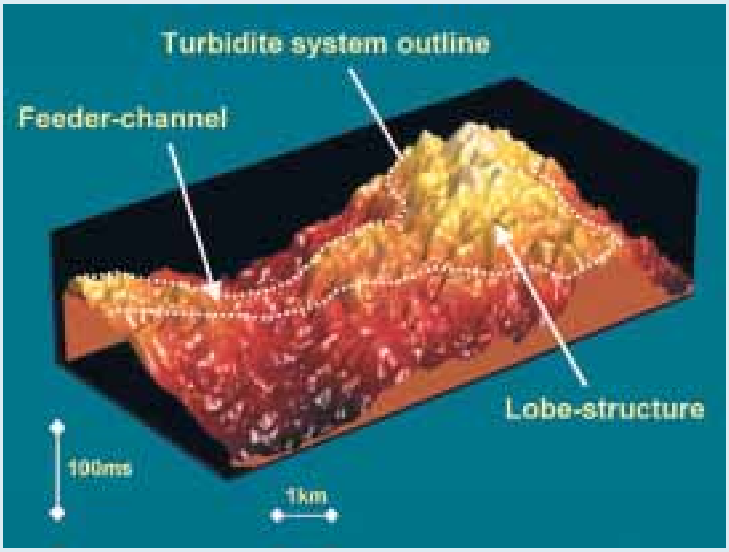
AVO crossplot analysis. The seismic section (top left) hides prestack information. By estimating AVO attributes from prestack seismic data it is possible to extract important information about hydrocarbons. The estimated AVO attributes are crossplotted against each other (right). By identifying the AVO anomaly off the background trend in the AVO crossplot (indicated by yellow colour in the right hand plot), one can investigate where this anomaly is located in the seismic cross section (lower left section). The anomaly is clearly confined to a structural high along this 2D section. This is a strong indication that the rocks are filled with of hydrocarbons.

even seismic processing and acquisition effects could cause false AVO anomalies. But in many of the failures, it was not the technique itself that failed, but incorrect use of the technique. Application of AVO analysis was therefore reduced.

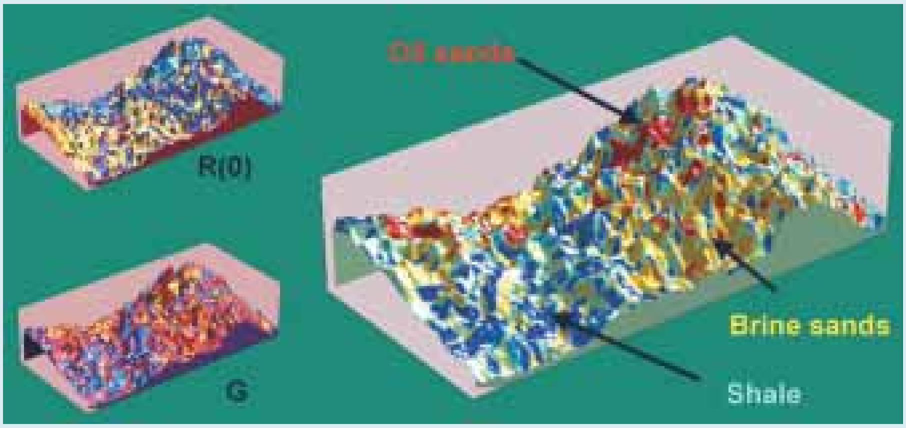
In the last decade we have observed a revival of the AVO technique. This is due to the improvement of 3D seismic technology, better pre-processing routines, more frequent shear-wave logging and improved understanding of rock physics properties, larger data capacity, more focus on cross-disciplinary aspects of AVO, and last but not at least, more awareness among the users of the potential pitfalls. The technique provides the seismic interpreter with information about pore fluids and lithologies, which complements the conventional interpretation of seismic facies, stratigraphy and geomorphology.



Example of AVO contour plots (R0 versus G) for different brine sands, oil sands and shales. The center contours represent the most probable location of the various facies and fluid types. Note the great overlaps and uncertainties between oil sands and brine sands.



Depth map to top reservoir of a North Sea turbidite system shows the outline of the submarine fan in the Glitne Field.



AVO attributes to the left (including R(0) and G) extracted from the top reservoir horizon and AVO classification results to the right. Note the prediction of oil sands in the structural highs of the turbidite system. Oil is produced from the lobe sands in the Glitne Field.

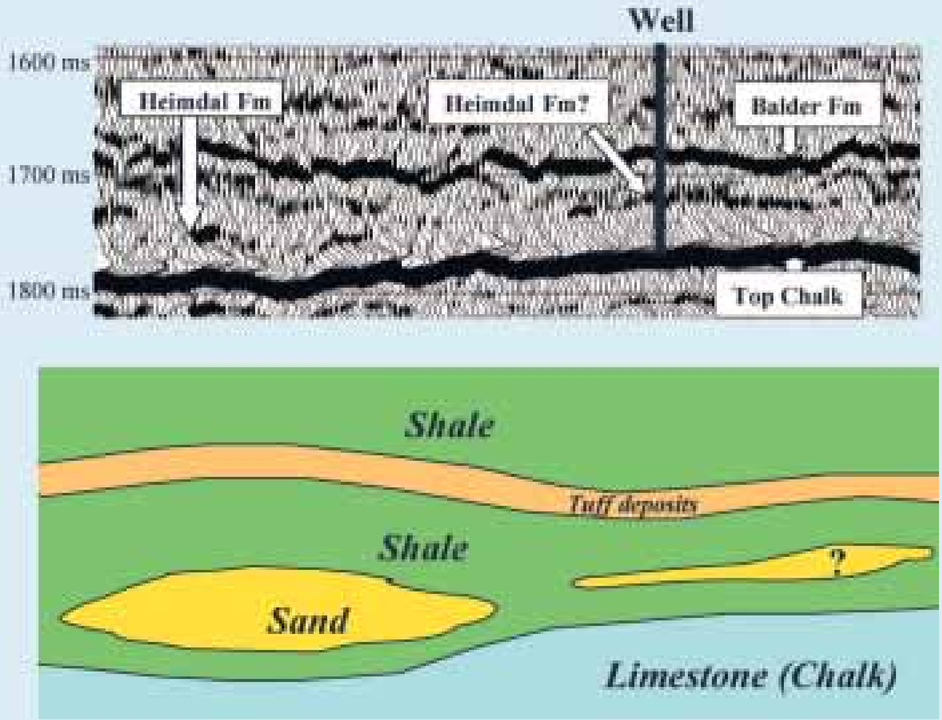
AVO analysis in a nutshell

The most common and practical way to do AVO analysis of seismic data is to make crossplots of the zero-offset reflectivity (R0) versus the AVO gradient (G). These attributes are estimated from pre-stack seismic gathers using simple least-square regressions.

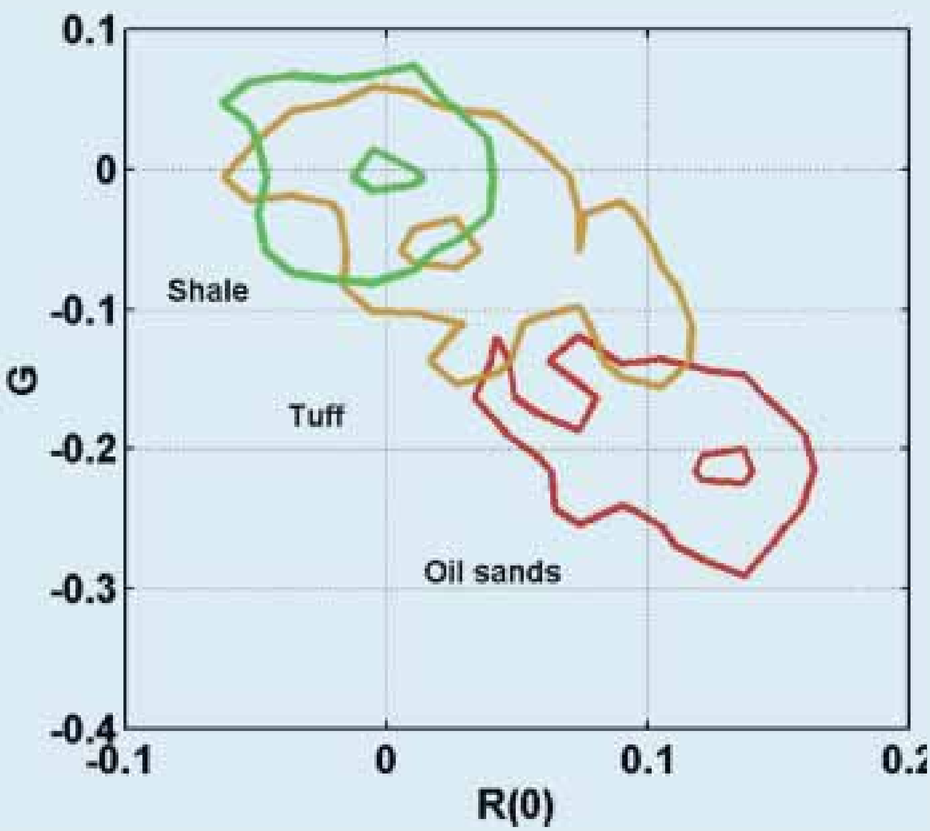
Brine-saturated sands interbedded with shales, situated within a limited depth range and at a particular locality, normally follow a well defined "background trend" in AVO crossplots. A common and recommended approach in qualitative AVO crossplot analysis is to recognize the "background" trend and then look for data points that deviate from this trend. The deviations from the background trend may be indicative of hydrocarbons, especially if these correspond to structural closures.

A problem with interpretation of AVO crossplots is that a given point in the crossplot does not correspond to a unique combination of rock properties. Many combinations of rock properties will yield the same R0 and G. Moreover, due to natural variability in geologic and fluid parameters, one given geologic scenario may span a relatively large possible outcome area in the AVO crossplot, not just a discrete point. Hence, a hydrocarbon-like AVO response might occasionally result from a brine associated reflection, and hydrocarbon saturated sands might not always produce an anomalous AVO response.

One way to account for this uncertainty is to create probability cross-plots of various categories of lithology and pore fluid scenarios. These can be based on statistical analysis of well log data and/or rock physics models. Each category is plotted as "contour maps", almost like topography maps. Here, the "mountain tops" represent the most likely location of a given class. It is very important to be aware that the contours of different facies and fluids are overlapping each other. This implies that an observed set of R0 and G can represent



Seismic stack section (top) intersecting the Grane turbidite sands. A well was drilled targeting a potential satellite sand (right side top and bottom). However, the well encountered volcanic tuff at the target level. The volcanic tuff gave a similar seismic response as the oil sands of the Grane sands.



AVO probability contours of shale, tuff, and oil sands in the Grane area. This figure illustrates the potential pitfall of tuff in the assessment of seismic amplitudes. The tuff data are between shales and oil sands. Hence, a tuff data-point can easily be mistaken for an oil sand, if we ignore tuffs and only try to distinguish sands and shales.

more than one category. This is one reason why AVO analysis can give wrong results. In addition, these crossplots are often affected by noise in the seismic data.

As mentioned above, AVO analysis can sometimes be successful and other times not. Below, three different case examples are shown, each of which had different degree of success.

The Good

The *good* example is where we successfully predicted the presence of hydrocarbons. This case is from the Glitne Field in the North Sea. Oil is predicted in the lobe channels using using AVO probability cross-plots analysis and has been confirmed by drilling.

The Bad

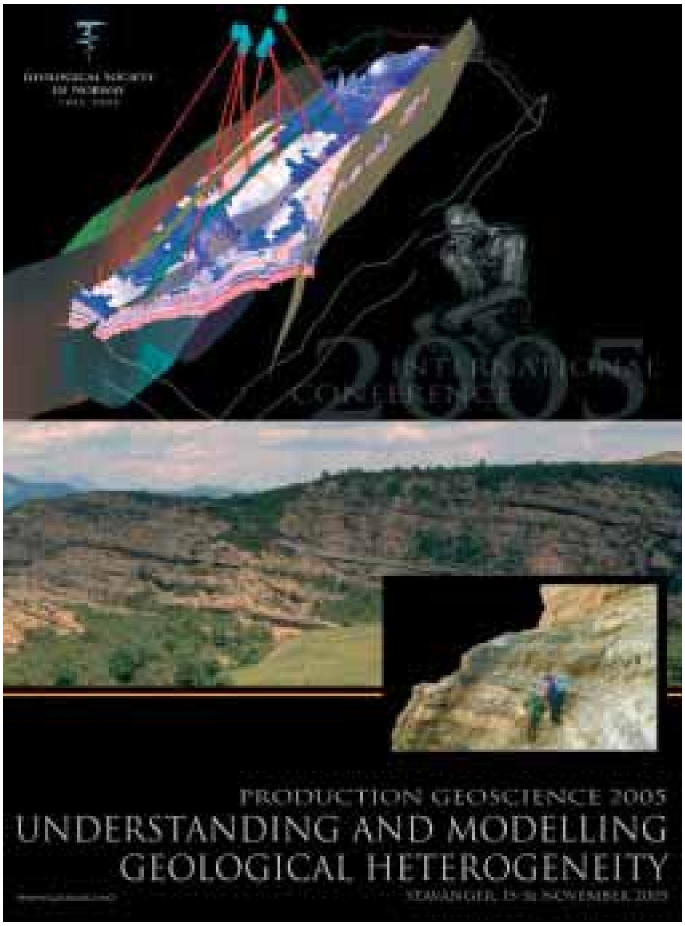
The *bad* AVO case is from the Grane area, also in the North Sea. In this case AVO analysis supported the presence of reservoir sands adjacent to the proven main reservoir body, but the model that was used neglected the presence of other lithologies than sands and shales. Post-drill analysis showed that the AVO method should be able to discriminate tuff from oil sands. Hence, it was not the methodology that failed. Insufficient information about the local geology was to blame.

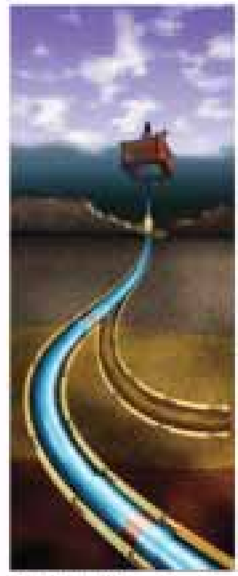
The evil

One of the most notorious pitfalls of AVO analysis is related to low gas saturation. This leads us to the *evil* case, where the AVO technique was unable to discriminate residual gas from commercial amounts of oil.

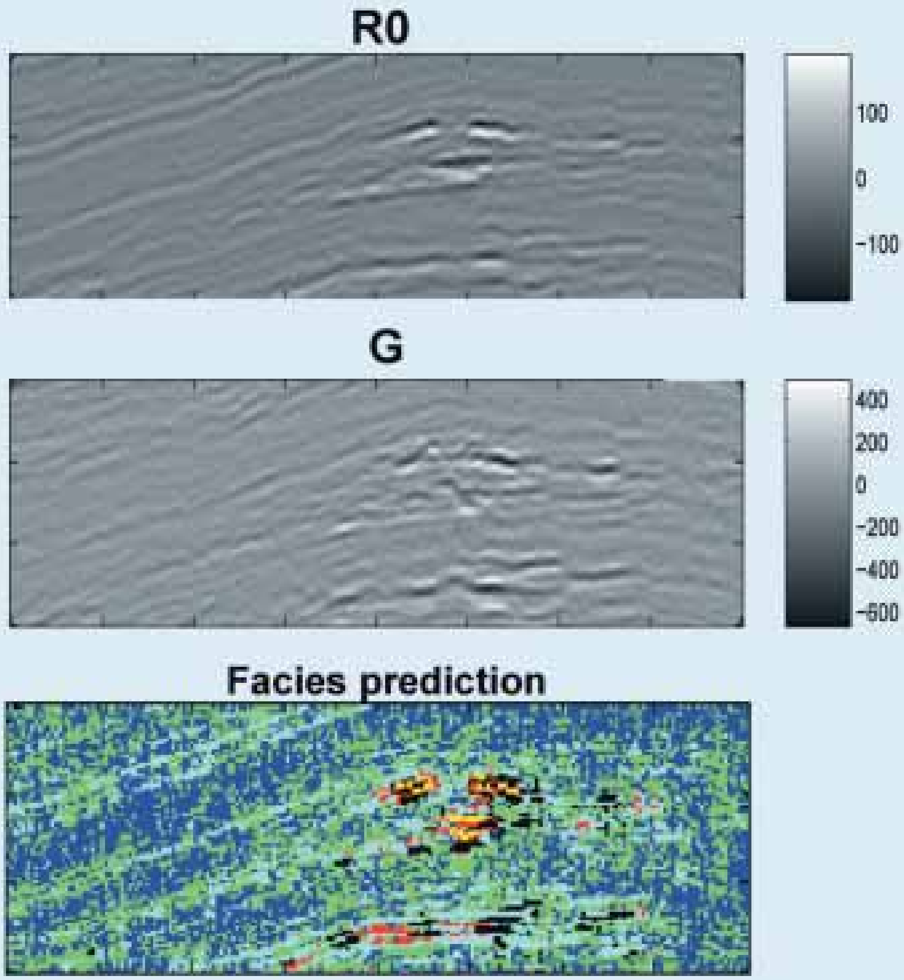
It is well known that just a small amount of gas in the pore space of a rock can cause a dramatic decrease in the stiffness of the rock. Therefore, residual gas saturations can give similar seismic properties as commercial gas saturations. If we are dealing with light oil, there may also be similar ambiguities between residual gas and commercial oil, or even residual oil and commercial oil. This is one of the main pit-falls in AVO analysis, even when the data are perfect and the information of local geology is excellent.

A seismic AVO anomaly offshore West Africa was the basis for defining a hydrocarbon prospect. However, the target only contained residual gas. The probabalistic AVO classification predicted the correct lithofacies, but was not able to discriminate residual gas from commercial amounts of oil.





Typical 125 scfm – 350 Barg Diesel Package for Seismic Applications



The upper two sections (R0 and G) show seismic anomalies from offshore West Africa. The anomalies were predicted to represent most likely oil and/or gas. The lower section shows AVO classification results (Blue=shale, green=heterolithics, cyan=brine sands, red=oil sands, yellow=gas sands, black=unclassified). The target zones were partially saturated with fizzy gas. In this case, the fizzy gas gave the same AVO response as commercial amounts of oil.

When is AVO useful?

Due to the many cases where AVO has been applied without success, the technique has received a bad reputation of not being a reliable tool. However, part of the AVO analysis is to find out if the technique is appropriate in the first place.

AVO will only work if the rock physics and fluid characteristics of the target reservoir are expected to give a good AVO response. This must be clarified before the AVO analysis of real data. Without a proper feasibility study, one can easily misinterpret AVO signatures in the real data. The feasibility study should be founded on a thorough understanding of local geology and petrophysical properties.

If we find that AVO analysis will work, and has the potential to detect hydrocarbons in the area of investigation, a new question arises: When should we do AVO analysis? Should it be done before, at the same time or after the conventional seismic interpretation and prospect evaluation?

During prospect evaluation it is common to do late-stage AVO analysis to strengthen the prospect, making it an ***AVO supported prospect***. Defining the prospects before doing AVO analysis means that potential prospects that would be detected only using AVO techniques can be missed. Fortunately, it is becoming more common for seismic interpreters to do interpretation on partial stacks.

Defining a prospect based predominantly on an AVO anomaly would create an AVO driven prospect. An ***AVO driven prospect*** needs a geological model that can explain the observed AVO anomaly. If the AVO work is done before there exists a thorough geologic interpretation in the area, it probably means that the geophysicist has made vague assumptions about the geologic input parameters in the first place. An AVO driven prospect can easily make the interpreter blind to pitfalls.

If AVO techniques are *integrated* with geologic interpretations of seismic data during prospect evaluation – ***geologically-controlled AVO analysis*** – it allows for more collaboration between the conventional seismic interpreter and the AVO analyst. The seismic interpreter can gain important input from the AVO analysis during the geometric interpretation, while the AVO analyst can get important input information to better constrain the rock physics models behind the AVO analysis.

Better cooperation

If we want to discover the increasingly more subtle oil fields in the future, a better interaction between conventional seismic interpreters and quantitative seismic interpreters must be established. This also means that the conventional seismic interpreter must become more knowledgeable in AVO analysis and other quantitative seismic techniques, whereas the rock physics and AVO analyst must become more knowledgeable in geologic aspects of seismic interpretation.

Acknowledgements

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Several of the figures in this article is taken from the book "Quantitative Seismic Interpretation" by Per Avseth, Tapan Mukerji and Gary Mavko, published by Cambridge University Press, 2005, see www.cambridge.org/0521816017 (see also GEO ExPro vol. 2, No. 2/3, page 66).