**Introduction**

In order to ensure the safety of its drilling operations while developing an important gas field in South East Asia, Total performed a large project of Shallow Gas Hazard identification with the help of CGGVeritas.

To reduce drilling risk around proposed sites during the development of the field, Total used complex integrated shallow gas risk assessment. It included standard AutoGasRisk methodology cross-validated with geological interpretation as in des Vallières (1996).

The AutoGasRisk (AGR) method is based on the interpretation of high-resolution mini 3D seismic datasets around the drilling site. It contributes to the drilling risk assessment by imaging gas charged bodies around proposed sites. It has been specifically designed to allow proper visualization of seismic anomalies along complex well trajectories. The engine of the AGR is an automatic and systematic screening of the 3D volume allowing the detection of anomalies, which is based on the reflection strength. Because of the very particular nature of the shallow gas and induced risks, it was decided to investigate an additional approach to complement AGR such as an analysis of the Amplitude Variations with Offset (AVO). Hopefully, this would allow predicting the nature of anomalies (gas charged body, lithology changes or indistinct).

Figure 1a shows shallow gas bubbling at the surface at a GTS site induced by drilling. The objective of AGR is to identify such risk prior to the Operations.

This paper presents this extra step, which has been recently added to the AGR method.

AVO techniques are known to be very sensitive to data quality issues. In our case (rivers and crossings, shallow water, production facilities, etc.) surface conditions are difficult. Despite huge efforts in acquisition and processing, data quality is not always up to the standards required for such an analysis. Hence, specific quality assessment has been integrated prior to the analysis. It is described in this paper.

![Figure 1a](image1a.png)

**Figure 1.** (a) GTS site showing shallow gas bubbling in surface induced by drilling. The objective of AGR is to identify such risk prior to the operations. (b) Dedicated seismic survey has been performed to assess shallow gas risk hazard on the given GTS: a High Resolution Square centered on the GTS and Standard Resolution Circle.
Operations
For the past 15 years, CGGVeritas has been performing AutoGasRisk for Total. It aims at mapping amplitude anomalies that can be interpreted as gas charged bodies. To perform this, either site survey or properly processed exploration data can be used.

In this project, dedicated seismic mini surveys were carried out on several Gathering Terminal Sites (GTS) to perform shallow gas hazard studies. For each one of the GTS of the field, CGGVeritas carried out a survey. It consisted into (Figure 1b):
- A High-Resolution Square (HRS)
- A Standard Resolution Circle (SRC).

The analyses of the two volumes are complementary and the results are cross-checked against a comprehensive visual examination of the entire HRS and SRC seismic volumes line by line. This last iteration ensures that no amplitude anomaly is missed. It enables the fine-tuning of anomaly detection and its classification using conventional attributes usually associated with shallow gas accumulation (phase reversal, frequency loss, pull-down, etc.). Those were compiled into a single comprehensive evaluation of the drilling assessment.

The two HRS and SRC volumes were processed using a “preserved amplitude” workflow allowing the generation of pre-stack attributes. These contain pre-stack migrated near and far angle substacks, intercept (Ro), gradient (Gr) and full stack. This data was further analysed.

Back to AVO basics
The classical works dedicated to AVO cross-plotting analysis (Rutherford-Williams, 1989 and Castagna-Swan, 1997) identified four types of gas sands based on their AVO characteristics. These can be summarized as follows (Figure 2):

Class I sands are characterized by higher acoustic impedances than those of the encasing shale. They are generally found in hard rocks at depth with lower porosities. They produced positive reflection coefficient, which decreases with angle.

Class II sands have almost the same impedance as the encasing shale. Hence they have moderate positive or negative reflection coefficient, which turns out to strong negative coefficient at larger angle. In some circumstances this implies phase reversal between near and far angle.

Class III sands have lower impedances than the encasing shale. They are very common in the shallow subsurface. Class III reflection coefficients increase in absolute value with increasing angle of incidence.

Class IV (added by Castagna-Swan after Rutherford-Williams) sands may have identical normal incidence reflection coefficients as per Class III, but the magnitude of Class IV sands reflection coefficients decrease in absolute value with increasing angle of incidence.

In this study, our aim is to highlight Class III behavior, since they are the most likely feature expected from gas charged sand bodies. Class IV sands are more difficult to highlight. This is particularly true with the technique used. It was therefore decided not to take into account class IV cases (see below). This is one of the limitations of proposed method.

In the geological context of our study, the shallow section is essentially composed of shales alternating with sands with occasional thin coals / lignite or carbonates layers. Coal and gas sand are lithologies acoustically much “softer” than shale. When thick enough, both produce high reflection strengths of identical polarity. They can easily be confused for one another.

Adding the AVO technique to the AGR procedure is motivated by the fact that coals have very different PR or Vp/Vs compared to shale’s properties. Gas sands are expected to have a much lower PR than encasing shales, whereas coal beds would typically be higher. Hence
shale/gas sand contrast would be Class III while coal/shale would behave as Class I. Such a distinction is uniquely brought up by AVO.

The AVO classification applies to reflection variation with angle (RVA) as opposed to Amplitude variations (AVO). The band limited nature of the propagating seismic wavelet makes an important difference between amplitudes and reflectivities. For non interfering contrasts, both are proportional to one another as long as wavelet bandwidth remains the same. Under such a limiting assumption, classification and derived cross-plot analysis schemes can be “exported” from reflectivities to amplitudes. However, this is not so obvious in more complex geological situations.

Idealized seismic responses can be seen as the reflection coefficients series convolved with the propagating wavelet. Hence, in the simplified context of isolated thin layers, reflectivity analysis can be transposed into amplitude analysis subject to wave shape constraints. This shall induce additional criteria to be looked at both at the time of processing the data and further when analyzing the extracted attributes.

**Impact of Seismic Wavelet on AVO response**

Let’s tame down the usual classification, expanding it into the case of seismic response. The basic model for a single interface or a thin layer implies dealing with similar waveforms at all angles (within a scalar, be it positive or negative), turning into $R_0$ and $G$ of similar wave shapes. This assumes seismic responses corresponded to identical source at all incidence angles. The two cases illustrated on Figure 2 correspond to idealized non interfering top and bottom responses for Class I to III Gas sands of Rutherford-Williams’ classification. In all cases, $R_0$ and $G$ have the same waveform (within a scalar, be it positive or negative).

- For Class I or II, $R_0$ and $G$ are reversed polarity. In our geological context, they are most likely due to lithology contrast (for example, lignite/sands). Such a situation shall be referred to as type LIT.
- $R_0$ and $G$ have the same waveform and polarity for Rutherford-Williams’s class III. In our context of shallow gas risk, such a situation is typically considered as indicative of potential gas presence. It shall be referred to as type GAS.

![Figure 2](image-url): Moving from RVA to AVO domain: AVO Class definition and expected waveforms for Intercept ($R_0$) and Gradient ($G$).
Impact of processing on AVO response

When processing artifacts are still present in the data such as poor NMO correction, bandwidth variations, multiple residuals or any other unexplained cause, apparent or “false AVO” effects are most likely introduced.

The best is to prevent such artifacts by an appropriate processing. Key aspects are:

- Velocity analyses are critical to get a reliable set of pre-stack data (Castoro, White, 2001) so that attributes extracted at different angle refer to the same geology.

- It is recommended that AVO analysis is performed with attributes extracted from constant aperture pre-stack data. Optimal angle mutes should be carefully selected after computation from smoothed seismic velocities in order to satisfy the condition throughout the area to be investigated, both spatially and vertically.

- Bandwidth variation with offset should thoroughly be considered in order to avoid its influence onto the AVO analysis. Most of the loss of the highest frequencies observed on farthest traces relative to the near traces is caused by NMO stretching (Dunkin and Levin, 1973). It critically modifies the way close by reflectors interfere. This is also referred to as “AVO tuning” (Lin and Phair, 1993). As the amount of stretching essentially depends on the incidence angle, working at constant angular aperture allows having a better control on bandwidth variations. Hence, frequency bandwidths of near and far angle stacks can be more easily harmonized.

Despite best efforts, residual artifacts are always present in the data, which should be further scanned to capture remaining flaws and reject corresponding measurements.

Unlike the simple situations depicted in Figure 2, presence of differential stretch and/or residual NMO yields mis-phased Intercept and Gradient waveforms: Ro and G shall be phase-shifted. This is schematically illustrated on Figure 3.

![Figure 3](image)

**Figure 3**: Processing artifacts generate Intercept and Gradient dissimilar waveforms that can be captured by locally estimating their relative phase difference.

Quadrature relative phase rotations induced on Gradient by poor NMO have been described by Swan (1991). Mis-phased Ro and G are given the type VEL as a reference to residual velocity errors.

Processing artifacts are not the only cause for such phase differences. It can also be caused by geology. However, such a situation is difficult to interpret, especially in the context of this study. This is a limitation of the proposed workflow. However, it is flagged as non-reliable for AVO analysis and therefore considered as indistinct in the risk assessment. Nonetheless, VEL typed Amplitude strength anomalies as seen by the conventional AGR are still evaluated in the risk assessment.
Focusing onto the right type of anomaly using Phase attribute

Only AVO effects clearly related to gas sand presence should be detected and described for the hazard they might represent to the drilling operations. It is therefore necessary to discriminate them from others, i.e. GAS from LIT and VEL types, which in this context would be assimilated to gas sand, coals and processing artifacts respectively.

Measurement of relative phase differences between intercept and gradient is an efficient way to locally characterize waveform differences. This can be easily implemented using the “Complex AVO Product” (CAVOP) which makes use of the analytical representation of the intercept (\(R_0\)) and gradient (\(G\)) signals (Tanner et al., 1979).

Considering their complex representations \(R_{an}\) and \(G_{an}\):

\[
\begin{align*}
R_{an} &= R_0 + jH_{R_0} \\
G_{an} &= G + jH_{G}
\end{align*}
\]

\(H_{R_0}\) and \(H_{G}\) are Hilbert’s transforms of intercept and gradient traces and \(j^2 = -1\).

As an extension to the usual AVO product \(R_0 G\), the Complex AVO Product can be formed as:

\[
CAVOP = R_{an} G_{an}^* = (R_0 + jH_{R_0})(G - jH_{G})
\]

This attribute is a complex number, which can be represented in the complex plane and parameterized by its modulus \(D\) and angle \(\Phi\) as sketched in figure 4.

Simple algebra would highlight the meaning of CAVOP’s modulus and angle:

- The angle \(\Phi\) estimates the relative phase difference between intercept and gradient. It is exactly equivalent to the difference between the instantaneous phases of the gradient and intercept. This quantifies a notion of shape difference between both AVO attributes.
- Modulus \(D\), is the magnitude of CAVOP. It is exactly the square root of the product of the envelopes of gradient and intercept. This qualifies the energy of both AVO attributes.

According to the above description, theoretical AVO responses for thin layers are expected to lay essentially on the horizontal / real axis. Potential artefacts would generate response away from the horizontal axis. This suggests a new scheme to characterize the three types (GAS, LIT and VEL) based on \(\Phi\) and \(D\) measurements:

- Zone of \(\cos(\Phi) > 0.7\) and high magnitude (\(D\)), for type “GAS”,
- Zone of \(\cos(\Phi) < -0.7\) and high magnitude (\(D\)), for type “LIT”,
- The remainder (-0.7 < \(\cos(\Phi) < 0.7\)) and high magnitude (\(D\)) can be assimilated to VEL type.

The threshold value of \(\Phi = \pi/4\) is such that \(\cos(\Phi)\) is close to 0.7. It was chosen based on empirical data from the field. These various areas are sketched in figure 5.

The benefit of using CAVOP is that it is robust relative to uncertainty on the absolute phase of the seismic source wavelet. Since the lack of similarity between intercept and gradient waveforms is a good indication of likely processing artifacts, it can be approached by the relative phase difference.

Note that CAVOP is only an intermediate computation designed for anomaly determination and has no physical meaning. It was used only for type determination (GAS, LIT or VEL) and came as an additional characteristic to the identified AGR anomalies based on the reflection strength.
A Real data example of such classification is shown figure 6. For all four intercept-gradient cross-plots, the magnitude D of the CAVOP attribute is presented by color. The initial input data (top-left) are divided into the three classes: GAS type (top-right), LIT type (bottom-left) and VEL type (bottom-right). The conventional application of AVO product RoG to highlight positive class III responses would pick points located in the first and third quadrant. Using the procedure presented here re-qualifies a fairly large number of such points into likely processing artifacts bringing robustness into the use of AVO.

Figure 5: Principles of identification of the three types defined for this project GAS, LIT and VEL using the Complex AVO product – The three types map into distinct areas of the complex plane of the CAVOP attribute.

Figure 6: Cross-plots R0-G. The hotter the color, the larger the magnitude of the CAVOP attribute. Initial input data points (top-left) are divided into the three classes: GAS type (top-right), LIT type (bottom-right).
Discussion and Conclusions

Although anomalous reflection strength is a primary attribute to detect shallow gas accumulations, which is rather robust and efficient, AutoGasRisk has its limitation. The reflection strength is still one of many attributes that can be used for geohazard study (phase reversal, frequency attenuation, velocity decrease, etc.). In addition, mini 3D seismic volumes sometimes do not represent a large enough volume, which allows the definition of statistical references to perform automatic screening.

This reason prompted for taking the AGR methodology one step forward with the use of AVO based attributes (Amplitude variation with Offset). This definitely brings additional value to the existing method at least because of the very strict data quality requirements. Additionally and in the geological context, the expected benefit is to minimize the impact of strong amplitude contrasts that can be readily attributed to lithological contrasts of shale/lignite as opposed to shale/gas sands while keeping robustness by identifying and ignoring the potential processing artifacts. The solution that has been found is to combine the two methods. The number of criteria has been increased, some of which simply relate to when not to use AVO in the evaluation. As a matter of fact, it decreases false detected anomalies considered to be shallow gas accumulations. It is implemented as an extension to the existing AutoGasRisk method of CGGVeritas.

AVO analysis is not a silver bullet which resolves all of the issues related to Gas detection. It is essential to limit its interpretation to validated and qualified seismic data within a known rock physics framework. Whatever the method used, the final word should belong to interpreters to avoid any ambiguity. Identified anomalies should have reliable geological shape and be cross-correlated with conventional approach (phase reversal, frequency attenuation, velocities decrease, etc.).

In summary, we should realize that the key to successful shallow gas risk assessment is an integration of all disciplines starting with acquisition through processing and data preconditioning for AVO analysis, AVO analysis itself cross-validated with interpretation result and finally drilling operations.

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References


