The impact of seismic amplitudes on prospect risk analysis

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Essentially all companies involved in oil and gas exploration and development must account for the various geologic risk factors associated with their specific prospects. Since seismic data (calibrated with well control if available) are a primary interpretation tool to determine these risk factors, the presence of seismic amplitudes that are potentially associated with oil or gas pays is extremely important. However, interpreters evaluating prospects have had to inherently know how seismic amplitudes impact the geologic chance factors and ultimately the probability of drilling success (Pg).

From 2001 to 2004, a DHI Risk Analysis Consortium of oil companies has been working to systematically quantify how seismic amplitude anomalies impact predrill estimates of Pg. This goal was accomplished by addressing specific seismic amplitude characteristics in different geologic environments, and by quantifying the quality of the data from which these interpretations are made.

Background. The conventional approach to determine Pg, which represents the chance of finding hydrocarbons in a reservoir capable of sustained flow, is to evaluate the geologic components required for a hydrocarbon reservoir to exist. The number of chance factors and specific definitions may vary slightly from company to company, but a commonly applied system of five factors is source, migration, reservoir, closure, and containment (Table 1). However, the presence of a seismic amplitude anomaly may have a significant influence on the risking of the geologic chance factors.

For example, the presence of a potential hydrocarbon-generated seismic amplitude anomaly may imply a working petroleum system, which would be strong evidence supporting the presence of source. A clearly defined seismic amplitude area also suggests that migration and trapping of hydrocarbons has occurred, that trap seals may be sufficient, and (depending on the geologic setting) reservoir rock may be present.

The above logic is of course "circular" in that the presence of an amplitude anomaly does not necessarily indicate it came from a hydrocarbon-charged reservoir. A better approach is to assess the confidence level that a seismic amplitude anomaly is truly generated from the presence of hydrocarbons by asking the following questions:

- How many HCI or DHI characteristics does the anomaly display?
- Should an amplitude anomaly of this type even be present in this geologic setting?
- In this geologic setting, should there always be an amplitude anomaly associated with trapped hydrocarbons?
- Are the seismic data being used to evaluate the amplitude feature of sufficient quality to make reliable interpretations and valid conclusions?

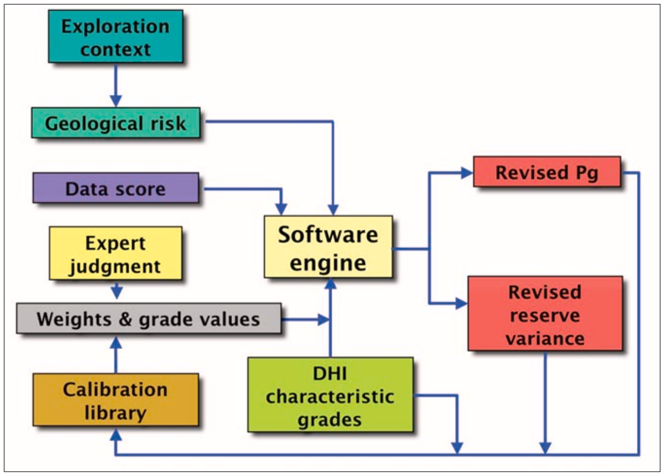


Figure 1. Interpretation workflow concept.

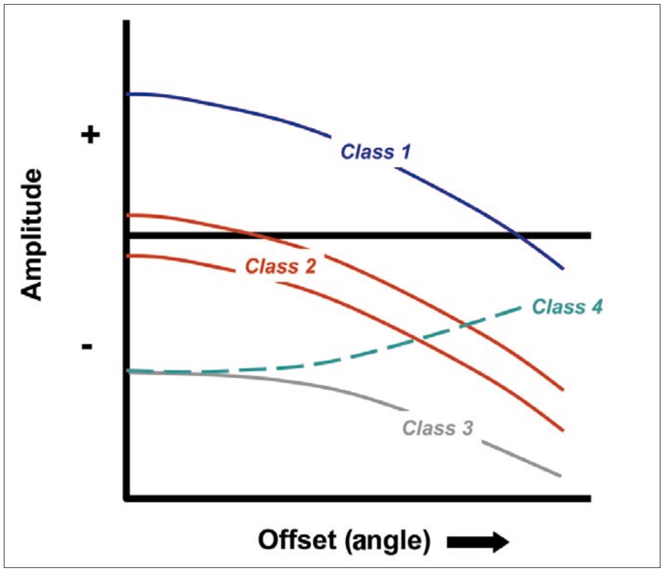
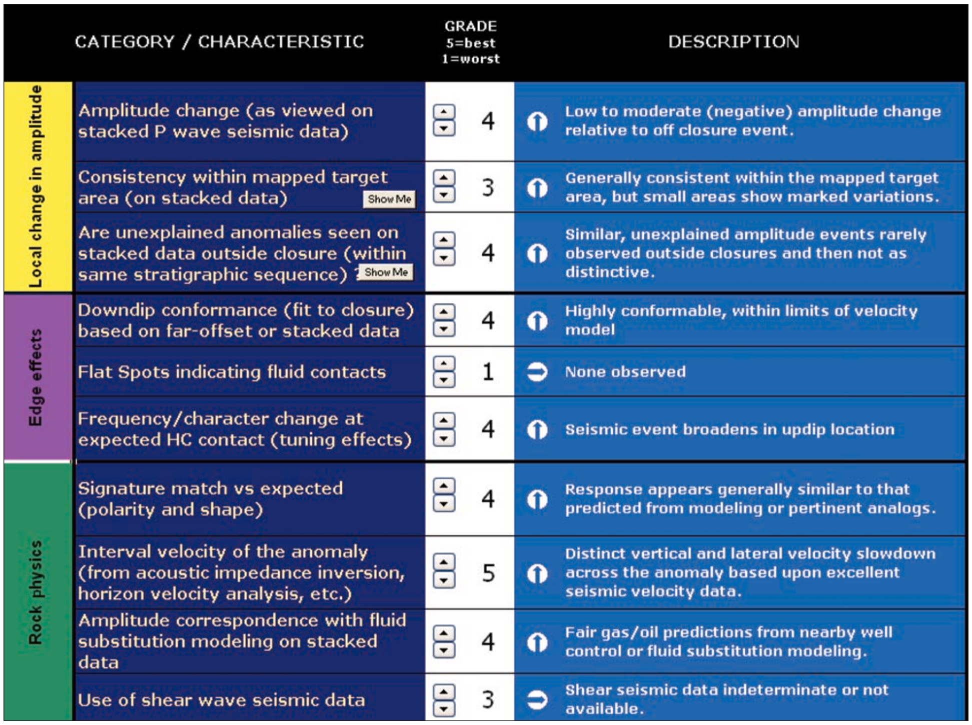


Figure 2. AVO classes based on amplitude change with offset from the top of gas sands (Rutherford and Williams, 1989; Castagna et al., 1998).

The methodology developed by the DHI Consortium addresses all these issues with an interpretation workflow concept (Figure 1) that has proven systematic, consistent, and produced very realistic results based on a calibration data set of almost 100 drilled wells.

Classifying seismic amplitudes. To determine which seismic characteristics are pertinent for specific geologic trends, it is necessary to classify hydrocarbon-generated amplitude anomalies based on their geologic setting. The consortium chose the classification approach of Rutherford and Williams (1989) based on three classes of AVO responses from the top of gas sands. With the addition of Castagna's (1998) class 4, essentially all geologic settings are accounted for in clastic environments (Figure 2).



	CATEGORY / CHARACTERISTIC	GRADE 5=best 1=worst	DESCRIPTION
Local change in amplitude	Amplitude change (as viewed on stacked P wave seismic data)	4	↑ Low to moderate (negative) amplitude change relative to off closure event.
	Consistency within mapped target area (on stacked data)	3	↑ Generally consistent within the mapped target area, but small areas show marked variations.
	Are unexplained anomalies seen on stacked data outside closure (within same stratigraphic sequence)	4	↑ Similar, unexplained amplitude events rarely observed outside closures and then not as distinctive.
Edge effects	Downdip conformance (fit to closure) based on far-offset or stacked data	4	↑ Highly conformable, within limits of velocity model
	Flat Spots indicating fluid contacts	1	→ None observed
	Frequency/character change at expected HC contact (tuning effects)	4	↑ Seismic event broadens in updip location
Rock physics	Signature match vs expected (polarity and shape)	4	↑ Response appears generally similar to that predicted from modeling or pertinent analogs.
	Interval velocity of the anomaly (from acoustic impedance inversion, horizon velocity analysis, etc.)	5	↑ Distinct vertical and lateral velocity slowdown across the anomaly based upon excellent seismic velocity data.
	Amplitude correspondence with fluid substitution modeling on stacked data	4	↑ Fair gas/oil predictions from nearby well control or fluid substitution modeling.
	Use of shear wave seismic data	3	→ Shear seismic data indeterminate or not available.

Figure 3. Amplitude characteristics for three categories of class 3 anomalies.

- Class 1: Very consolidated sands (porosity <15%) that typically have gross interval velocities >12 500 ft/s (3650 m/s). These reservoir sands have higher impedance than the encasing shale with the density contrast having a greater effect on the AVO response. These reservoirs are usually found onshore in hard rock geologic settings (e.g., mesozoic and paleozoic rocks).
- Class 2: Less consolidated sands than class 1, but more consolidated than class 3. These moderately compacted sands (porosity 15-25%) are found offshore and onshore. Gross interval velocities of the sands are typically between 8500 and 12 500 ft/s (2650-3650 m/s). The acoustic impedance of the gas sand and the encasing shale are about equal.
- Class 3: This is the typical "bright spot" or "DHI" setting where unconsolidated reservoir sands are encased in higher impedance shales, usually of Tertiary age. These reservoirs commonly have porosities >25% and contain gas or high GOR oils. Gross interval velocity of these sands is usually <8500 ft/s (2650 m/s). Class 3 targets were initially found exclusively offshore but, due to higher quality seismic data, are now being observed more frequently onshore.
- Class 4: Unconsolidated sand similar to class 3, but overlain by high velocity hard shale, siltstone, or carbonate. Shear-wave velocity in this overlying hard interval is larger than that of the gas sand (this situation is opposite for all other classes).

It is important to realize that the boundaries between classes are gradational and therefore it may be necessary to evaluate amplitude anomalies in two classes.

To put the prospect in its proper geologic context and to preserve the case for future comparisons, it is necessary to document the prospect's location, well class (e.g., development, wildcat), type of closure, terrain (onshore/offshore), depth-to-target, water depth, expected reservoir size and thickness, etc. The expected reservoir geologic characteristics such as age, lithology, lateral geometry, and vertical boundaries are also input along with the presence and location of analog fields and discoveries.

Assessing the base geologic risk. The interpreter estimates initial Pg based on regional and local geologic interpretation which ignores the seismic amplitude anomaly. Thus, the initial Pg is based on environment of deposition studies, reservoir isochore (isopach) maps, structural and/or stratigraphic maps from wells and seismic, etc. In other words, the geologic chance factors in Table 1 are risked *without the seismic amplitude anomaly being considered*.

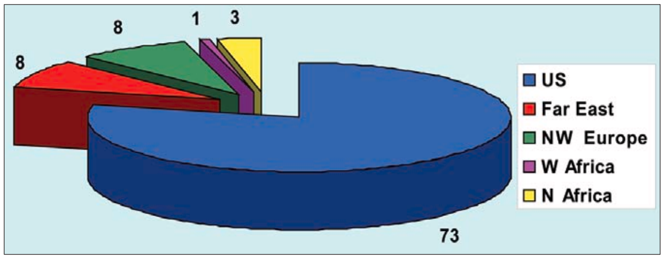


Figure 4. Locations of drilled prospects in the DHI Consortium database.

Table 1. *Typical geologic chance factors*

Source rock	fetch area and thickness
	richness
	thermal maturity
	type
Migration and timing	closure forms before/during migration
	migration distance and pathways
Reservoir rock	facies and extent
	minimal thickness
	reservoir quality
Closure	confidence of depth/shape of closure
	structural and stratigraphic traps
	confidence in mapping
Containment	sealing capacity/top and bottom
	preservation

Typically, initial Pg will be very low if the prospect is a pure stratigraphic trap where the location of the prospect is only identified by the amplitude anomaly and will be high

Table 2. *Seismic data quality factors*

Type: 2D, 3D, single component, multicomponent
Processing/migration: poststack time, prestack time, poststack depth, prestack depth
Imaging quality: focusing, defocusing, raypath geometries, etc.
Acquisition and processing vintage
Type of processing: speculative to specifically shot for prospective reservoir
Amplitude preservation
Line and trace spacing (2D)
Bin size (3D)
Maximum far offset (2D, 3D)
Phase of data
Vertical resolution: tuning thickness
Horizontal resolution: relationship to size of amplitude anomaly
Prestack data: gathers (meters or feet), angle gathers, offset or angle volumes, AVO, angle (θ) or $\sin^2\theta$ graphs, intercept versus gradient crossplots, etc. • amplitude preservation on gathers (gaining) • sufficient offset and/or angles for AVO analysis • accuracy of offset angle calculations • reflectors clearly distinguished from coherent and random noise • proper NMO correction • anomaly trend well defined on graphs and crossplots

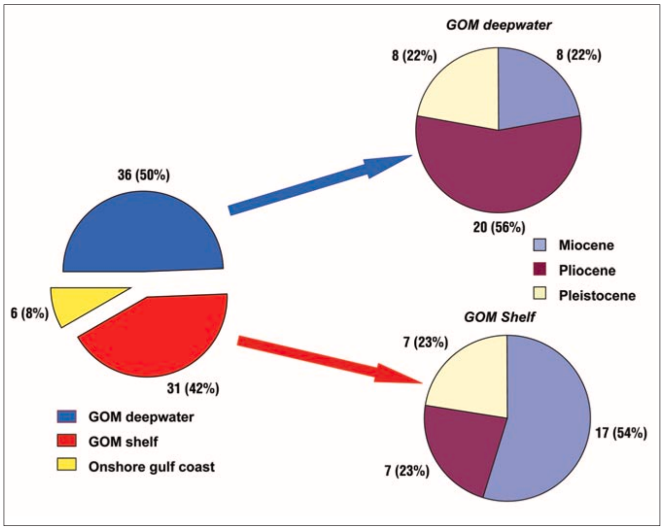


Figure 5. *Location of drilled U.S. prospects in the DHI Consortium database.*

if the prospect is in a development setting with significant well control. Initial Pg is a very important anchor point because, depending on how the interpreter answers questions about data quality and amplitude characteristics of the anomaly in the following steps, initial Pg will be modified positively or negatively to get the final or revised Pg.

Measuring data quality. In order to properly risk seismic amplitude anomalies, it is necessary to evaluate the quality of the seismic data and nearby relevant rock physics information. The interpreter categorizes the seismic data, velocity and density information, and modeling and computes a data quality score which ranges from 0-100%. Most data quality values are in the range of 40-85%.

Quite often, more than one seismic data set is used to interpret an amplitude anomaly on a prospect; therefore, the assumption made here is that the highest quality seismic data are employed to make the final interpretations. Table 2 lists the seismic data quality factors. Of particular significance are the type of processing/ migration and the vintage of the seismic data. For example, the amplitude preservation of prestack depth-migrated data (e.g., wave equation) in the late 1990s is not as good as that available using today's algorithms. In addition, seismic data acquired and processed for large speculative group seismic surveys quite often have insufficient acquisition and processing parameters (migration velocities) to accurately image amplitude anomalies for specific prospect evaluation. Most modern 3D surveys have sufficient bin size to properly image amplitude prospects, but 2D data will always have out-of-plane resolution limitations. Knowledge of the phase of the data (optimally zero phase) is extremely important for amplitude evaluations with both prestack and poststack data.

Our industry has numerous types of prestack data and products; however, essentially all are based on the original trace gathers and their associated acquisition parameters and processing. Intercept versus gradient crossplots, fluid factor displays, or AVO hodograms are all a function of the trace gather parameters, quality of the processing, and the distinction of signal from noise on the data.

For rock and fluid property data, the quality and proximity of known density and velocity (P- and S-wave) information is extremely important because it relates to the interpreter's confidence level of the associated acoustic response of the prospective anomaly. The depth, stratigraphy, and depositional environment of this information in relation to the amplitude feature have a direct bearing on evaluating the prospect. Knowledge of the pressure environment of the amplitude prospect is also important because the acoustic response of gas sands in a pressured environment is not the same as in the shallower normal pressured section of the sediment column. Finally, modeling and fluid substitution (such as HCI modeling, AVO modeling, or multicomponent modeling) may have an important bearing on the confidence level in the interpretation of the rock and fluid properties.

Quantifying the amplitude characteristics. Depending on the AVO classification (1-4) for a specific prospect, the interpreter will answer questions about a multitude of amplitude characteristics on a scale of 1-5 (worst to best). Each possible response is described and the specific response

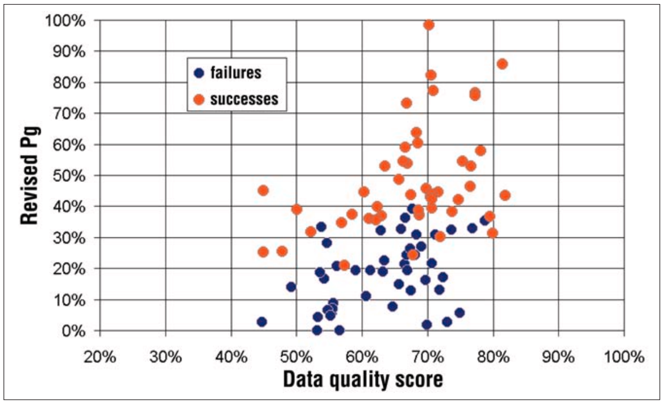


Figure 6. Revised Pg versus data quality score color-coded by the well outcome.

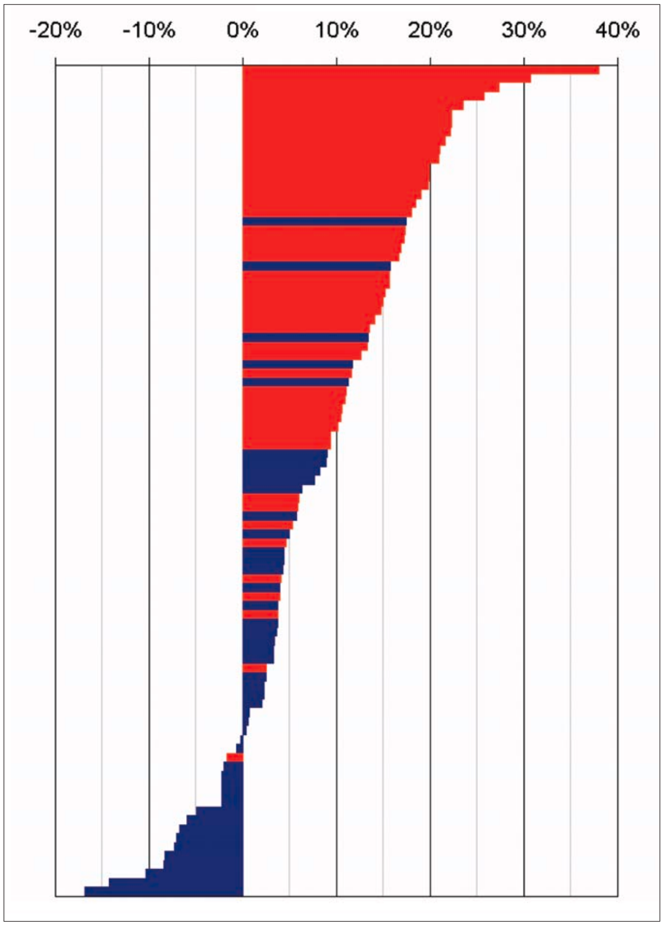


Figure 7. The delta Pg (difference between initial Pg and revised Pg) segregated by successful wells in red and dry holes in blue.

chosen is scored and weighted to determine how Pg will be revised before the data quality score is included. The consortium has developed an extensive list of pertinent amplitude characteristics; the list ranges up to 36 characteristics for class 3 anomalies and drops to 25 for class 1 anomalies.

To assist the estimator, the amplitude characteristics are organized into nine categories: local change in amplitude, edge effects, rock physics, primary AVO effects, AVO attribute crossplots, amplitude anomaly interpretation pitfalls, vertical and lateral context, seismic analogs, and containment and preservation. Figure 3 is an example of characteristics associated with the first three amplitude categories (for class 3 anomalies) and related responses by an interpreter.

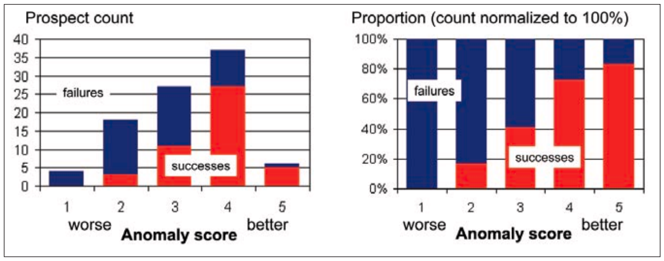


Figure 8. Histograms of the raw data (left) and normalized responses (right) for the consistency in mapped target area characteristic. The well outcome is color-coded.

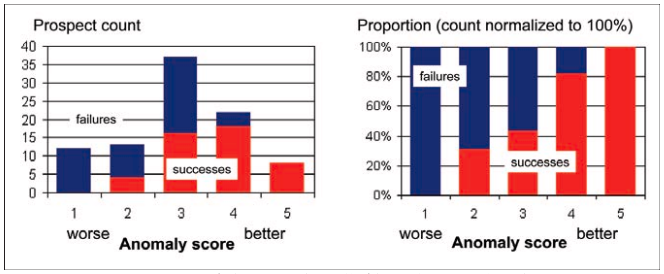


Figure 9. Histograms of the raw data (left) and normalized responses (right) for the downdip conformance (fit to closure) based on far offset or stacked data characteristic. The well outcome is color-coded.

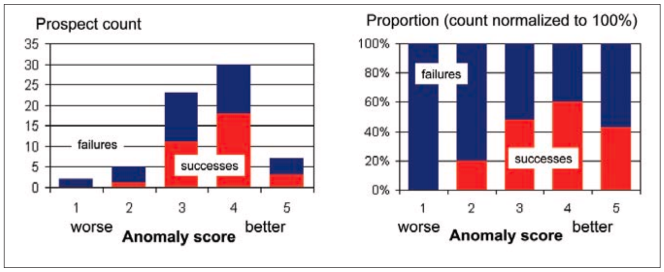


Figure 10. Histograms of the raw data (left) and normalized responses (right) for the change in AVO compared to model (wet versus hydrocarbon-filled) characteristic. The well outcome is color-coded.

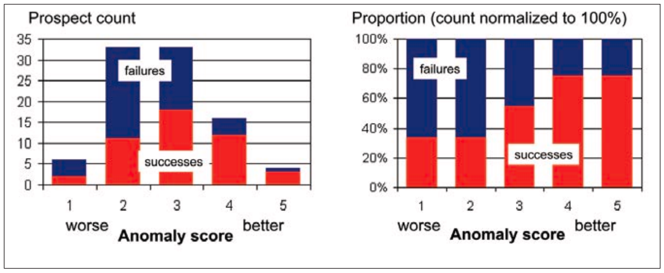


Figure 11. Histograms of the raw data (left) and normalized responses (right) for the high porosity clean wet sands pitfall characteristic. The well outcome is color-coded.

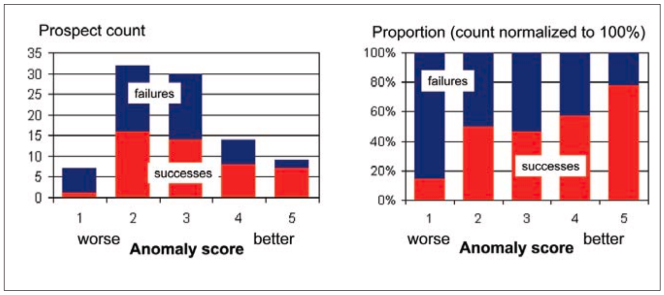


Figure 12. Histograms of the raw data (left) and normalized responses (right) for the wet reservoir with low gas saturation pitfall characteristic. The well outcome is color-coded.

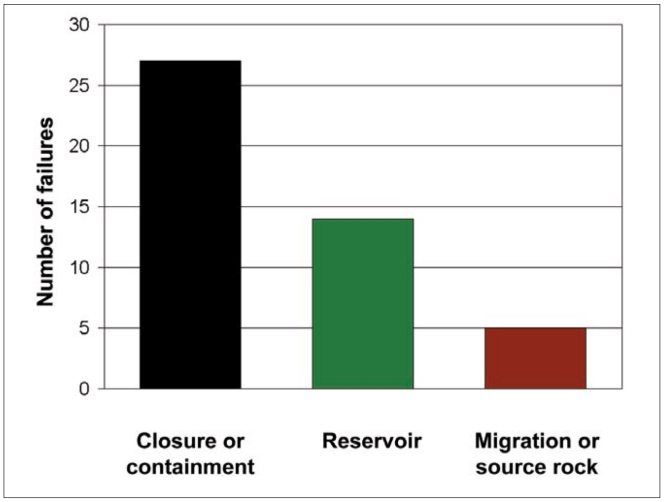


Figure 13. Geologic chance factor failure modes for the 46 dry holes in the database.

Database and results of drilled prospects. From 2001 to the spring of 2004, 18 member oil companies contributed information from 93 drilled prospects to help establish a workflow and database of amplitude-related prospects used in the determination of Pg. Members contributed prospects from a wide variety of prospect types from geologic trends around the world, but in all cases they provided the pertinent information necessary to determine the Pg of the amplitude-related prospect based upon the information that was known at the time the well was drilled. Of these drilled wells, 46 were dry holes and 47 were successful. Figure 4 displays the location of these prospects, which were predominantly from the United States, but also included prospects in northwest Europe, Far East, West and North Africa. The breakdown of the U.S. prospect settings is shown in Figure 5.

The scatter plot of Figure 6 displays the revised Pg, (i.e., the revised probability of geologic success after the data quality and amplitude characteristics have been determined) versus the data quality score. The success (red) or failure (blue) of the wells are color coded. Note that there were no dry holes that had a final Pg of over 40%. In fact, the average final Pg for the dry holes was 20%, whereas the average final Pg for the successful wells was 48%. The data also indicate that there were no successful wells that had a revised Pg of less than 20%. There is a slight trend suggesting better data quality relates to successful wells.

The histograms of Figure 7 display how much the initial Pg was modified (delta Pg) after the amplitude-related prospects were evaluated for data quality and amplitude characteristics. This information is further segregated by the outcome of the individual wells. The database also indicates that any well with a positive delta Pg of approximately 20% or greater was a successful well. By the same token, over a third of the dry holes had a negative delta Pg. This display relates the confidence level that the amplitude anomaly evaluated truly is generated by hydrocarbons, and the detrimental effect of not having an anomalous event when, according to empirical observations along trend or modeling efforts, that one should be present.

Impact of amplitude characteristics. In an effort to determine the significance of the amplitude characteristics to the success of a well, histograms were generated from the raw scores for each characteristic, color-coded based on the outcome, and normalized to 100% to determine any trends. Figures 8-12 show histograms for five characteristics and their associated trends.

Figure 8 displays the responses and trend for the consistency in mapped target area amplitude characteristic which is in the local change in amplitude category. This characteristic relates to how laterally consistent the amplitude anomaly appears in the mapped target area on stacked data. In other words, is the amplitude feature consistently present in the mapped closure or does the amplitude appear spotty? As the normalized histogram suggests, there is a strong correlation between the rating of the responses for this characteristic and the successful outcome of the wells.

One of the most important amplitude characteristics is the downdip conformance (fit to closure) on far-offset or stacked data (Figure 9). This characteristic describes how well the amplitude anomaly correlates to the downdip structure of the prospect. If the amplitude is truly related to the structural closure, there should be a good correlation at the downdip limit. A significant factor in making this interpretation is whether the maps are in depth or time, presence of velocity variations, stratigraphic variations, and imaging quality of the seismic data (e.g., migration).

A standard approach to interpret AVO features is to model nearby wells substituting hydrocarbons in wet sands and vice versa, in an effort to understand the AVO response for prospective reservoirs. Typically Gassmann fluid substitution approaches are employed to model the seismic response to fluids in sands. The histogram of Figure 10 displays the responses of the change in AVO compared to model (wet versus hydrocarbon filled) characteristic. There is a definite positive trend for successful wells with high scores related to this characteristic.

In the amplitude anomaly interpretation pitfalls category, one of the many pitfalls identified by the consortium is the possibility that the anomaly was caused by high porosity clean wet sands (Figure 11). Depending on the geologic setting, high porosity clean wet sands can produce amplitudes that are at times difficult to differentiate from hydrocarbon-generated features. Knowledge of sand responses from well control in the area, fluid substitution modeling, and local depositional models can help determine the appropriate response for this characteristic.

Another important potential pitfall in interpreting seismic amplitudes is the possibility the feature was generated by a wet reservoir with low gas saturation (5-10% gas). As Figure 12 indicates, there is a positive trend of successful wells with a better anomaly score for this characteristic. The interpretation of low gas saturation has long been a problem in the unconsolidated portion of the sediment column because a small amount of gas can generate prominent reflecting amplitudes. It is very important to understand not only the geologic setting, but also the pressure environment in which the prospect is located because the amplitude response of low gas saturation sands under high pressure is different than in the shallow part of the sediment column. Seismic amplitudes generated by hydrocarbons in a high pressure environment tend to not generate dramatic amplitude increases at low gas saturation levels.

Failure modes. At the conclusion of the consortium in 2004, 46 dry holes were in the calibration database. Figure 13 breaks out the failure modes for these dry holes based on the five geologic chance factors. Closure and containment (seal capacity) were the most significant interpreted causes for failure with 27 wells (59%). It is at times difficult to differentiate structural and stratigraphic closure problems from seal related issues, which is why these two geologic chance factors were grouped together. The lack of reservoir quality rock accounted for 14 of the dry holes (30%). Failures related to this geologic chance factor included siltstones, condensed zone, marls, top of hard pressure, and soft shale between two "tite" sands. The failures due to migration and source rock factors seen on 5 dry holes (11%) included issues such as heavy oil and coal.

Conclusions and future. Formed in 2001, the DHI Risk Analysis Consortium has provided a forum to apply the collective wisdom of dozens of experienced geoscientists from 18 different oil companies as well as several consultants, to the problem of systematic and objective seismic amplitude prospect evaluations. By the end of 2004, the consortium had recorded in their archive predrill and postdrill data on 93 prospects evaluated by this process, a database difficult to duplicate in the industry. With the consistent application of this process and continued compilation of additional prospects, a database of significant size will enable accurate and definitive statistical information for calibration.

In 2005, the consortium is continuing to add prospects to the database and is developing a methodology to determine how seismic amplitudes affect the determination of productive area and thickness variables in prospect reserve calculations.

Suggested reading. "Amplitude-versus-offset in gas sands" by Rutherford and Williams (GEOPHYSICS, 1989). "Framework for AVO gradient and intercept interpretation" by Castagna et al. (*TLE*, 1998). "Fizz water and low gas-saturated reservoirs" by Han and Batzle (*TLE*, 2002). "Rudiments in performance tracking, with special emphasis on amplitude-bearing prospects" by Roden and Citron (presented at 2004 SEG Annual Meeting workshop on Uncertainty in Reservoir Prediction and Reservoir Risk Analysis). TLE

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