QUANTITATIVE INTERPRETATION
THE AIM OF QUANTITATIVE INTERPRETATION (QI) IS, THROUGH THE USE OF AMPLITUDE ANALYSIS, TO PREDICT LITHOLOGY AND FLUID CONTENT AWAY FROM THE WELL BORE

This process should make use of all available data, assist in risk assessment, account for uncertainty and ultimately foster confidence in the predictions.

01. QI workflow 2B for exploration and appraisal. The comprehensive workflow assimilates geology, geophysics, petrophysics, rock physics and uncertainty. Simultaneous inversion products are quantitatively integrated with statistical rock physics models to make probabilistic, volume based fluid and lithology predictions using a Bayesian framework. Interpretation of the probability volume outputs can be easily digested by the decision makers, maximising business impact.
DUG offers two major product lines with respect to Quantitative Interpretation services. The different offerings are tailored to suit the amount and type of input data that is available and what study objectives are required to be met. Each of these products can be applied to both 2D and 3D seismic data.

**QI ROAD MAP**

**Reconnaissance**

1. No well control within the seismic
   - A. NO REGIONAL WELLS EXIST
     - AVA attributes (including AVA stack rotations)*
   - B. RELEVANT REGIONAL WELLS EXIST
     - Statistical rock physics, stochastic modelling, AVA attributes (including AVA stack rotations)

**Exploration and Appraisal**

2. Well control within the seismic volume or on one or more 2D lines
   - A. LIMITED WELL CONTROL
     - Statistical rock physics, stochastic modelling
     - Relative simultaneous (AVA) inversion, AVA stack rotations to highlight lithology / fluid effects
     - Map-based probabilistic lithology and fluid prediction
   - B. GOOD WELL CONTROL
     - Statistical rock physics, stochastic modelling
     - Absolute simultaneous (AVA) inversion
     - Volume-based probabilistic lithology and fluid prediction

*DU's EE equivalent
Elastic properties are influenced by depositional environment (lithology type), fluid content and local geological trends (compaction/burial history).

Geological trends are important in areas with poor well control for interpretation away (lateral and vertical) from wells. Quantifying depth dependence imposes meaningful geologic trends which constrain uncertainty and the expected range of rock properties and seismic responses. End-members are defined as the ‘cleanest’ examples of the lithologies present, based on an interpretation of all relevant well logs. This is indirectly based on mineralogy. End-member intervals are picked, up-scaled and cross-plotted to form depth-dependent trends (Figure 3). Interpretation of end-members permits subsequent forward modelling of different lithology and fluid combinations via mixing. Interpreting end-members also constrains uncertainty (Figure 4).

A rock physics model should predict the elastic properties of a potential lithology:

- Away from well control
- At any depth
- Whether or not it has been penetrated
- With various fluid scenarios (where applicable)
- With various reservoir qualities

03. Depth dependent statistical rock physics model capturing the inherent scatter of elastic rock properties for end-member lithologies (sand in red and shale in green).

04. Comparison between end-member trending and the application of petrophysical cut-offs to quantify the inherent scatter of elastic properties. Interpreted end-member sand and shale picks are shown in red and green respectively. Sand picks using a VClay cut-off are shown in blue. Note that the scatter on the blue picks is much greater and the fitted trend is approximately halfway between the end-member sand and shale. Uncertainty is greatly overestimated using the blue picks and the true end-member properties have not been captured.
Seismic amplitude and rock property forward modelling is performed stochastically (Monte Carlo simulation), to capture the expected range of responses for all candidate lithology and fluid combinations over the depth range of interest.

**Stochastic Forward Modelling**

Stochastic forward modelling can answer questions such as:

- What type of AVA and amplitude response should I expect?
- Does AVA aid in the discrimination and prediction of fluid and lithology?
- What amplitude responses do we expect to see on full stack data?
- What is the range (uncertainty) in the expected response?
- Given the observed inherent scatter in end-member rock properties, can we discriminate between different lithology and fluid combinations in rock property space?
- How do all of the above change with depth, fluid and lithological variations?

This utilises the depth-dependent, end-member, statistical rock physics model and involves end-member mixing and Gassmann fluid substitution. Fundamental outputs of the stochastic modelling are multivariate probability density functions (PDFs) for each lithology fluid combination - quantifying the inherent scatter in rock properties and range of seismic responses at every depth.

**Stochastic Modelling Results**

Stochastic forward modelling results over a 600 m depth range. Each ellipse represents the two standard deviation contour around the fitted PDF (from 10000 realisations) for the given lithology and fluid combination at a given depth. Red is a gas sand, blue is a brine sand and grey is a shale. Ellipses are shown at 100 m depth increments. The ability to discriminate between different lithologies and fluid content can be interpreted. Note that at shallower depths (to the left) the shale is softer than the brine sand. Moving deeper the shale becomes harder than the brine sand on average. This depth dependent change in properties (and also seismic response) is captured by the rock physics model.
DUG Spike® is a constrained simultaneous inversion toolkit that quantifies the elastic rock properties that result in the observed AVA present in seismic data.

The fundamental constraints are the seismic match and the elastic property misfits outside the seismic bandwidth. These constraints are critical to avoid noise in the inverted impedance variations and ensure that the inverted impedance perturbations contain frequencies which can be reliably predicted. Additional geophysical constraints such as rock physics covariance constraints on inverted reflectivity can also be utilised.

The absolute inversion optimises the solution for elastic properties (P Impedance, S Impedance and density) given initial low frequency impedance model(s) and the seismic data. The relative inversion optimises the solution for AVA coefficients (intercept, gradient and curvature) using only the seismic data. The outputs of the relative inversion are in true reflection coefficient units.

Calibration, comparison and QC of inversion results to the existing well log data are important parts of the workflow. This follows a detailed well tie and wavelet extraction workflow. A state of the art multi-angle, multi well Bayesian wavelet derivation program is used to estimate the wavelet and its uncertainty (seismic noise level). It utilises a fully integrated Bayesian approach to the coupled uncertainties in wavelet estimation.

A proprietary proven toolkit is utilised for building low frequency models. The model building toolkit is flexible and has a number of options to suit specific requirements and input data availability. At the core of the toolkit are advanced 3D geostatistical workflows which incorporate all available information, producing a stable model away from the well (background trend), while honouring the well information. DUG Spike® products can be quantitatively integrated with the expected results (PDFs) from the statistical rock physics workflow to generate lithology and fluid probability volumes.

**FEATURES OF DUG Spike® INCLUDE:**

- Simultaneously invert elastic properties at every trace location using any number of input seismic angle stacks
- At each trace a constrained non-linear optimisation is solved
- Both pre- and post-stack seismic data can be input
- Derive band-limited (or relative) and absolute impedance
- Laterally- and time-varying wavelets are supported (if required) for each angle stack
- The Aki-Richards three-term approximation is used to constrain the inverted AVA coefficients
- Other absolute rock property outputs can also be derived including Vp/Vs, Poisson’s ratio, Lambda-Rho and Mu-Rho
- No assumptions about Vp/Vs are made during the inversion
- Invert a single post stack seismic volume for P Impedance (or acoustic impedance)

06. Example of the interactive calibration interface (at a well location) for simultaneous inversion and lithology and fluid prediction.

07. Absolute acoustic impedance (AI) tie at a well location after inversion.
AVA stack rotations are DUG’s equivalent to Extended Elastic Impedance (EEI) and are designed to help discriminate between different AVA responses.

A stack rotation is equivalent to a weighted stack of two AVA attributes, such as near and far angle traces. Figure 8 illustrates the concept with respect to a seismic gather. Different stack rotations can be defined to optimally enhance or suppress particular types of AVA. Inputs can be seismic angle stacks or inverted elastic impedance. AVA stack rotations using relative impedance data have the advantage that the wavelet effects (such as tuning) have been optimally removed, improving the general interpretability.
AVA STACK ROTATIONS

The calibration and interpretation, when possible, is based on statistical rock physics modelling.

Figure 9 is an example. The comparison of forward models and observed data allows interpretation of the observed AVA stack rotation results within the interpreted rock physics model framework. It may be possible to create optimal stack rotations which optimally enhance fluid and lithology effects respectively, as shown in Figure 10. Of course stack rotations can be performed on data and interpreted more qualitatively - without well data or a rock physics model for calibration. DUG Insight allows the user to animate through multiple realisations (ie different stack rotations) of a dataset which is obviously of great benefit for such analyses. Stack rotations at the relevant angles can be compared in an effort to interpret fluid and lithology effects.

09. Variation in reflectivity as a function of AVA stack rotation angle for three different interface models. Notice in this case that at around -60 degrees the gas response is enhanced relative to the brine and shale responses.

10. AVA stack rotations can be used to optimally highlight fluid and/or lithology effects. In this case a particular AVA stack rotation is used to highlight a fluid anomaly which is not obvious on the input angle stacks. The far stack data is shown in (a). (b) shows the stack rotation using seismic angle stack data as input. (c) shows the same stack rotation using relative elastic impedance data, which has removed the wavelet effects.
Using derived petrophysical interpretations, deterministic AVA synthetics can be calculated for different fluid scenarios.

Gassmann fluid substitution is used to generate elastic logs for the different fluid cases. Deterministic modelling provides an understanding of the variation in expected seismic response at the well locations for different fluid scenarios and can be compared to the population behaviour described by the stochastic modelling results.
The use of a Bayesian classification framework enables prior geological knowledge to be incorporated into a probabilistic prediction, capturing uncertainty and quantifying risk.

Bayesian updating is used to make quantitative predictions based on inverted seismic data and stochastic rock physics models, generating lithology and fluid probability volumes. Multivariate rock property probability density functions are created using stochastic forward modelling of depth-dependent elastic rock physics models. These are quantitatively compared to equivalent inverted data to make predictions.

12. Qualitative comparison of the inverted rock properties with the modelled PDFs from the appropriate depth. The P-Impedance and Vp/Vs data shown in section on the left is crossplotted on the right. Three polygons have been drawn on the section and the corresponding points have been highlighted in their respective colours on the crossplot. The orange polygon captures an anomaly with low impedance and Vp/Vs. The blue polygon captures the down-dip part of this anomaly. The purple polygon captures the bounding lithology. The modelled PDFs on the crossplot (represented by the two standard deviation contour ellipses) are for a gas sand (red), brine sand (blue) and shale (grey). It is clear that at this depth there is good agreement with the observed data and the modelled data. The anomaly is consistent with what we expect for a gas sand at this depth.

13. Each sample in the inverted rock property volumes can be quantitatively compared with the modelled PDFs (representing the possible lithology and fluid combinations) for the depth of that sample. Using a Bayesian classification scheme the probability of that sample being any one of the possible lithology and fluid combinations can be calculated. In this way, lithology and fluid probability volumes can be calculated for the entire inversion volume.
The initial QI study was based on four previously drilled dry holes. Over twelve significant gas discoveries have now been made. New discovery wells are in close proximity to old dry wells. Reservoir models were built based on the probability volumes.

14. Gas probability data provided confidence to drill downdip of a 12 m brine sand resulting in the first discovery. Red indicates high gas probability.

15. The above discovery well was drilled at 67° to successfully intersect multiple gas probability anomalies. P-impedance data shown on left. Gas probability data shown on right.

16. Fifth discovery well shown on arcline. Red indicates high gas probability. The discovery well is in close proximity to an existing dry well.

For a more detailed description of this case study and others, go to www.dug.com/case_studies/.