PS An Integrated Approach Using Geotechnology to Unlock the Secrets of Low Permeability Reservoirs*

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Abstract

One of the most significant developments in the oil and gas industry for the last decade was the tremendous economic success in the development of the unconventional shale plays in the United States. Advances in horizontal drilling, reservoir characterization, completion, interpretation and extraction methods from unconventional plays such as the Barnett, Marcellus, Haynesville and Fayetteville have grown rapidly and started to play a major role in the natural gas production in the USA. The experience gained in early years is helping to unlock resources in more unconventional plays in North America, resulting in significant growth of shale gas resources across the continent.

North American success has sparked a worldwide interest in development of shale gas reservoirs. There are increasing interest and exploration activities to unlock unconventional resources by both multi-national E&P companies and government entities in Europe, South America, Asia-Pacific and the Middle East. Unconventional exploration in areas outside North America is in its early stages, and can be accelerated by adopting best practices learned from North American experience and applying the right technologies to explore these plays.

Experience gained in developing unconventional resources in North America has led to the development of a formation evaluation workflow specifically designed for evaluation of these complex reservoirs. This integrated workflow combines petrophysical, geological characterization and geomechanical analysis and applies the results to both the pilot hole and lateral drilling programs and completion strategies.

This presentation describes the application of these techniques in US shale plays as analogues to worldwide unconventional reservoir exploitation. By incorporating fracture stimulation design and performance results with formation evaluation datasets the overall economic viability of low permeability reservoirs is achieved.

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Marcellus Shale – An Example of a Vertical Pilot Well Integrated Analysis

I. Abstract

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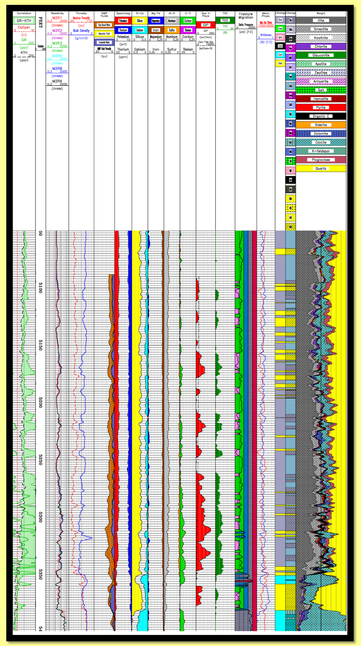

Figure 1- Geochemistry Tool Analysis

II. Methodology (cont.)

Geochemistry data (**figure 1**) obtained from the mineralogy tool helps to determine TOC, reduces uncertainty in porosity calculations and identifies lithofacies.

Nuclear Magnetic Resonance data (**figure 2**) provides a mineralogical independent total and effective porosity, pore size distribution, and shale volume and distribution.

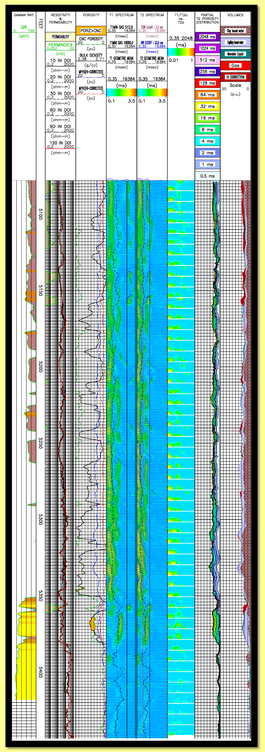

Figure 2 - NMR Data Analysis

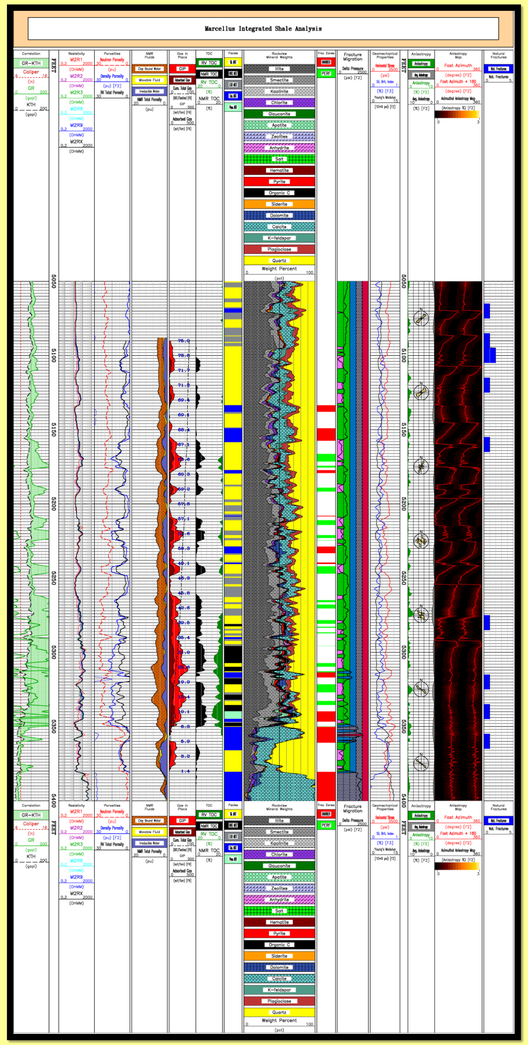

Figure 3 – Integrated Analysis

III. Result

Integrating the information (**figure 3**) from petrophyics, geochemistry, geology and geomechanics will help develop a model to determine GIP, OIP, economics, the "sweet spot" and lateral well targeting.

II. Methodology

Unconventional Reservoirs present many challenging issues when trying to characterize the reservoir as well as developing a completion strategy. Workflows for meeting these challenges have been developed in recent years. In this study we evaluated three wells from different basins and applied three different approaches for solving specific issues associated with unconventional reservoirs.

The Marcellus suite of logs is an example of a workflow developed for characterizing a vertical well to define the "sweet spot" and aid the selection of the kick-off point for the lateral well. Many parameters are necessary to evaluate an unconventional reservoir, including the mineral composition, total organic carbon present, kerogen type and maturity, as well as "conventional" petrophysics, total hydrocarbon in place, structural geology including natural fractures and faults, and geomechanical rock properties.

A workflow for characterizing a lateral well and planning a completion strategy is illustrated in the Barnett example. High resolution resistivity images are acquired while drilling to aid in optimizing the packer placements to avoid geological hazards and identify quality reservoir rock.

The Niobrara illustrates an example of a vertical wellbore with a workflow that has been developed for unconventional plays, but in this example an additional component of deep shear imaging is illustrated to aid in defining the "sweet spot" and lateral well placement .

Additionally, a seismic characterization workflow has been developed to aid extrapolation and mapping of characteristics across the whole reservoir for sweet spot delineation.

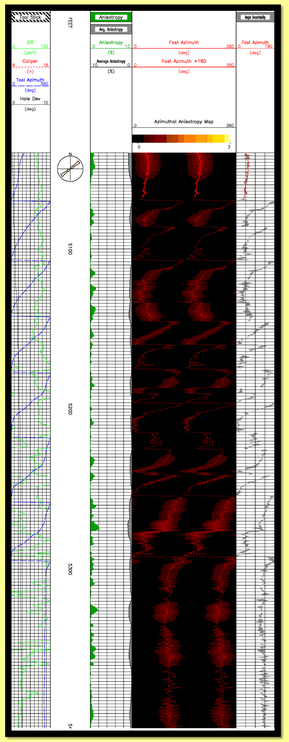

Figure 4 - Dipole Acoustic Data Analysis

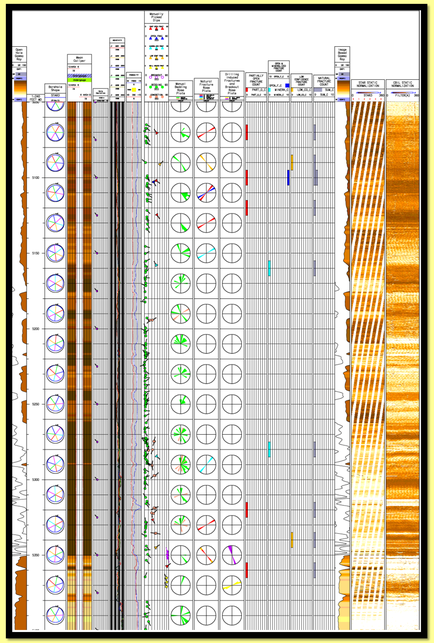

Figure 5 - High Resolution Resistivity and Acoustic Image Analysis

II. Methodology (cont.)

High Resolution Resistivity and Acoustic images (**figure 5**) provide important geological information for structure, natural fractures, and faults. In addition, one must consider if the fractures contribute to permeability, porosity and connectivity or, do the fractures have a negative impact on the reservoir, do they act as baffles or barriers to hydrocarbon flow. Geomechanical data may be acquired by identifying drilling induced fractures and borehole breakout on the images, representing present day in situ stress orientation.

Dipole acoustic data (**figure 4**) provides geomechanical parameters including minimum horizontal stress, Poisson's ratio, Young's modulus, and fracture migration. Brittleness indicators may be computed from mineralogy and geomechanical brittleness and hardness. Fracture initiation indicators are computed from minimum horizontal stress and lithofacies.

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Barnett Shale – An Example of a Vertical Pilot Well to Lateral Well Integrated Analysis

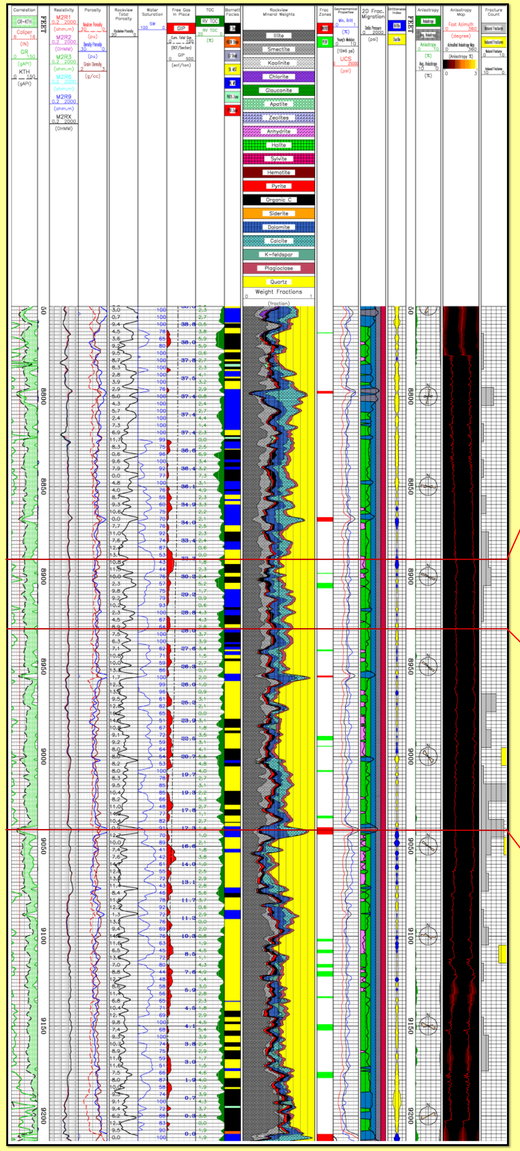

Figure 1 – Integrated Shale Analysis from Vertical Pilot Well

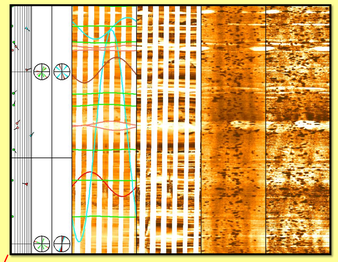

Image 1A – Simultaneous Acoustic and Resistivity Image

Image 1A identifies natural fractures and concretions. The cyan tadpoles and sine waves are representing mineralized natural fractures. The red tadpole and sine wave are interpreted as partially open natural fractures. A shear fracture is interpreted by the small offset in the bedding, represented by the brown tadpole and sine wave. A few concretions are also interpreted, these are represented by the pink sine waves and tadpoles.

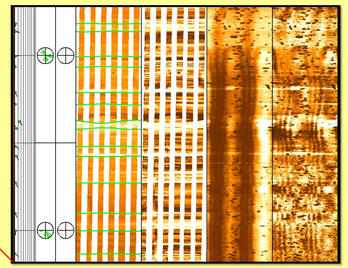

Image 1B – Simultaneous Acoustic and Resistivity Image

The green tadpoles and sine waves on **Image 1B** above are bedding picks. This interval was selected as the chosen lateral target due to its distance from water bearing formations below, TOC of 4%, and good fracability.

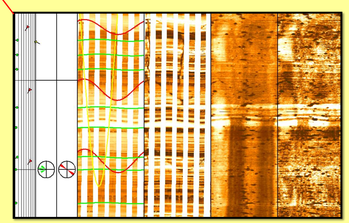

Image 1C – Simultaneous Acoustic and Resistivity Image

In **Image 1C** a drilling induced fracture indicating the near wellbore in situ maximum horizontal stress, is interpreted on the resistivity image illustrated by the yellow tadpole and sine wave. A bright high resistive zone in the middle of the image above correlates to the fracture barrier on the integrated plot.

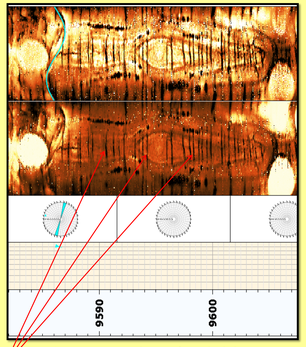

Image 2A – LWD Horizontal Resistivity Image

The transverse drilling induced fractures identified on **Image 2A** are an indication of anisotropy. The anisotropy identified should be considered when designing the completion for this stage compared to a stage with isotropic rock.

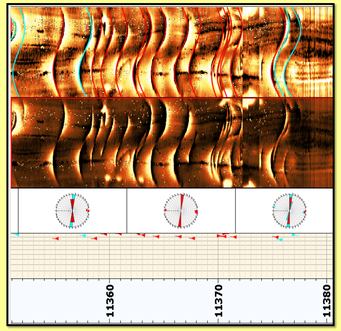

Image 2B – LWD Horizontal Resistivity Image

Image 2B is an isotropic zone with a dense natural fracture count. The interval is considered isotropic due to the lack of transverse or longitudinal drilling induced fractures. The cyan blue sine waves and tadpoles are representing the resistive fractures displayed in this interval. The red sine waves and tadpoles are representing a mixed resistive and conductive signature on the images.

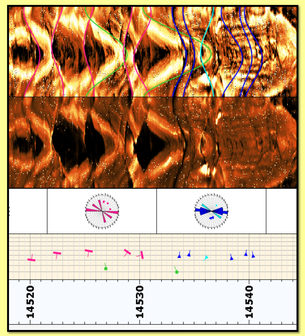

Image 2C – LWD Horizontal Resistivity Image

Image 2C above is highly faulted as indicated by the offsets in the bedding planes. The green sine waves indicate bedding and the magenta sine waves are the fault planes. This stage needs to be treated with caution due to the faulting.

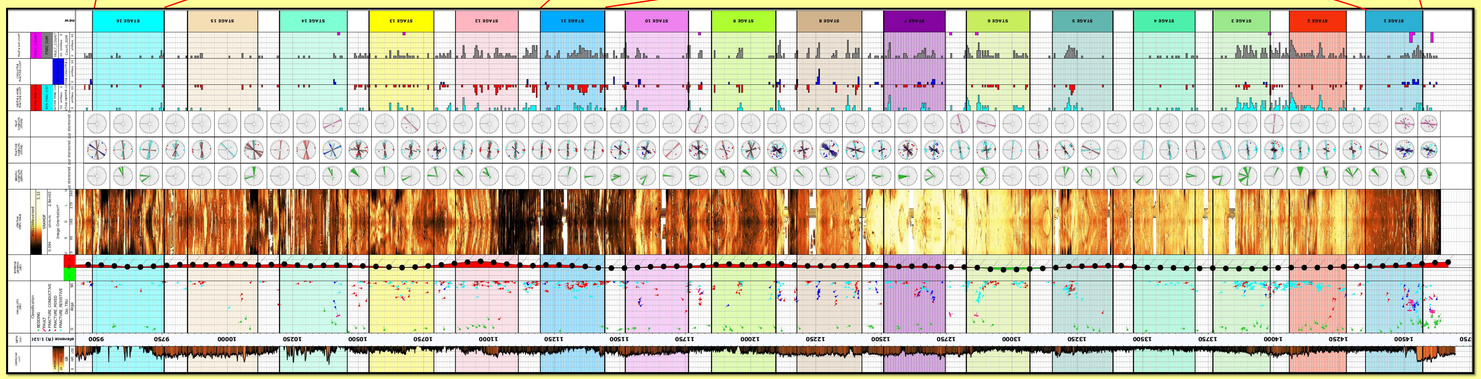

Figure 2 – LWD Resistivity Image Interpretation with Hydraulic Fracture Stages

Once the lateral is drilled the determination of natural fractures (**Image 2B**) and faulted zones (**Image 2C**) play a major role in determining the placement of packers and stages. Once the "Sweet Spot" is identified from the integrated shale evaluation the next step is to target that zone with a horizontal well. Borehole images acquired while drilling the horizontal have become a very important step. These borehole images help visualize the fractures and faults through the wellbore. Characterization and orientation of fractures and faults can be critical to targeting or avoiding zones for stimulation. Identifying drilling induced fractures (**Image 2A**) in the horizontal can also give us a qualitative picture of the geomechanics of the rock. Borehole images in the horizontal well are the only way to identify any hazards to the production of the well.

The horizontal image interpretation (**figure 2)** can be exploited in multiple ways to enhance stimulation. The borehole image interpretation can be used for stage selection, stage length, number of stages, perforation spacing, types of fluid and proppant, and the amount of the fluid and proppant. All of this will maximize the effectiveness of the hydraulic fracture treatment, which at the end of the day will improve production.

At the reservoir level the results of the image interpretation can be combined with micro-seismic data (not shown) to have better predictability from well to well.

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Niobrara Shale – An Example of a Vertical Pilot Well Integrated Analysis with Deep Shear Wave Imaging

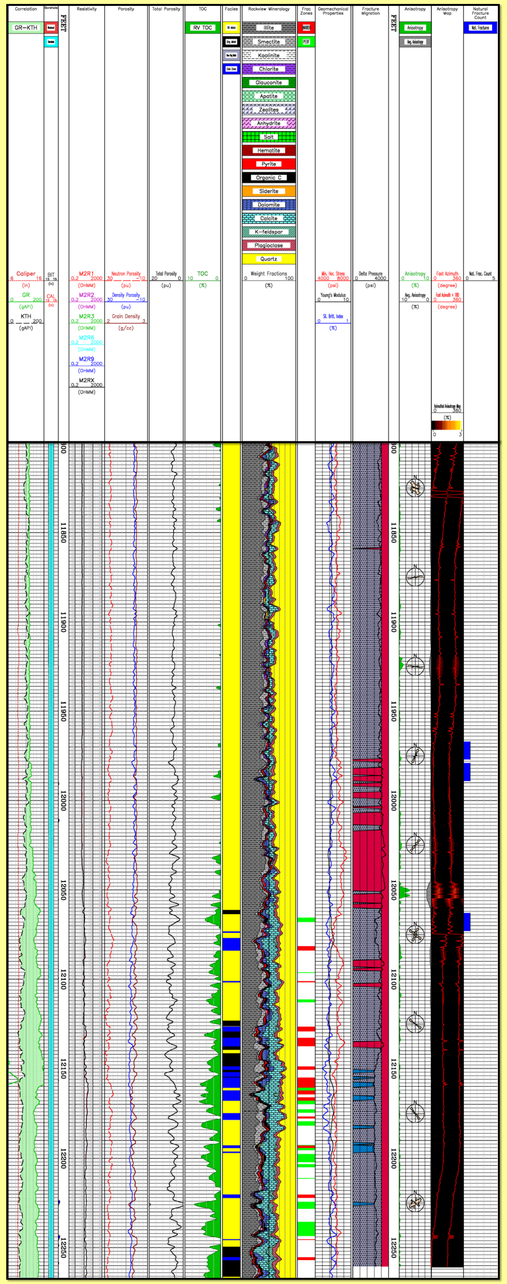

Figure 1 – Integrated Analysis

The borehole images that were acquired in this Niobrara Integrated Analysis (**figure 1**) only indicate a few natural fractures. The acoustic anisotropy is less than 2% in this interval except for one section at 12050 feet. Deep Shear Wave Image processing was applied to better interpret the fracture network in this case study.

DEEP SHEAR WAVE IMAGING

Utilizes cross dipole measurements to determine two orthogonal planes of investigation for near vertical fracture system detection.

The depth of investigation can be up to 75' away from the borehole.

Utilizes standard seismic depth migration techniques of time based dipole waveform data to determine fracture distance away from the borehole.

Data is oriented from true north so that fracture amplitude is maximized in one of the planes of investigation, which determines the direction from the borehole of any existing fracture system. The fracture system geometry must be properly oriented in 3-D space to allow the transmitted dipole energy to be reflected back to the dipole acoustic Tool receiver array.

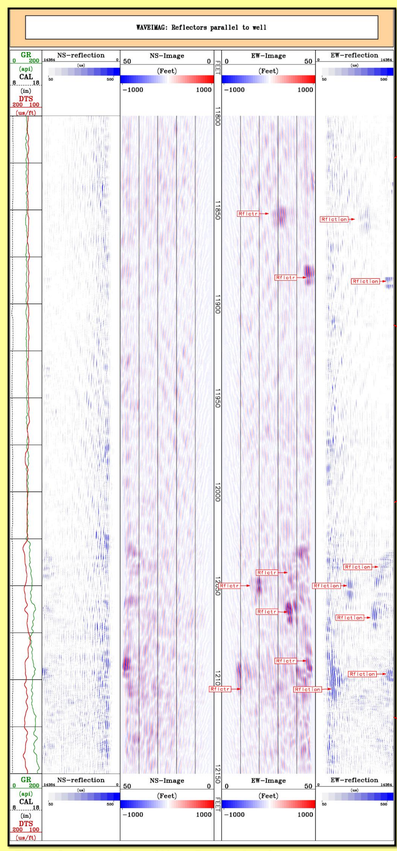

Figure 2 – Deep Shear Wave Processing Analysis

Deep Shear Wave processing (**figure 2**) potentially indicates a cluster of sub-vertical features around 12050 ft. – 12100 ft. These features appear to strike NNW-SSE.

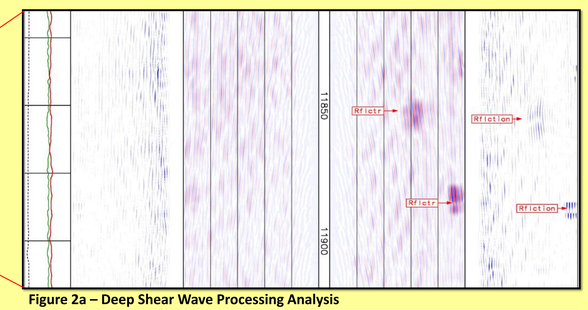

Figure 2a – Deep Shear Wave Processing Analysis

The sub-vertical features above (**figure 2a**) are potentially fractures that strike NNW-SSE. These features are located ~35-45 feet away from the wellbore.

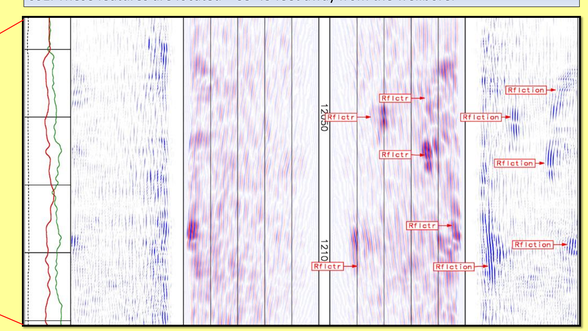

Figure 2b – Deep Shear Wave Processing Analysis

The sub-vertical features above (**figure 2b**) are potentially fractures that strike NNW-SSE. The features are located from ~10 – 45 feet away from the wellbore. The identification of these features will aid in the planning and strategy of the completion design.

Integrated Seismic-Wellbore Characterization Workflow

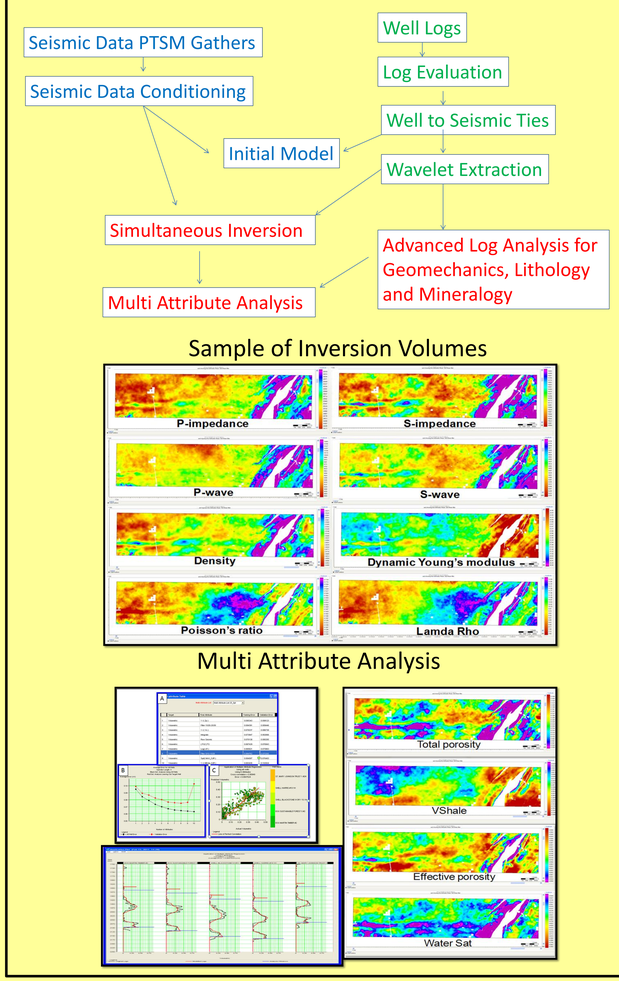

Figure 3 – Seismic Characterization Analysis (modified from Hampson–Russell , CGG)

Large variances in the shale reservoirs, both laterally and vertically, impact the production, decline rates and ultimate recoveries. Each play has "sweet spots" with certain geologic, geomechanical and geochemical characteristics that are manifested in higher production rates and/or ultimate recoveries.

An integrated geophysical-geological solution (**figure 3**), which combines advanced integrated wellbore formation evaluation analysis with the analysis derived from seismic simultaneous inversion processing and advanced attribute analysis based on 3-D seismic data sets, allows to identify "sweet spots" and move from statistical drilling to targeted, sweet spot drilling, ensuring optimum return on investment from each well.

Advanced integrated wellbore formation evaluation analysis (**figure 3**) provides near wellbore anisotropy, lithology, mineralogy, TOC, saturations, porosity, mechanical properties, fracture characterization and identification of stratigraphic sequences & lithofacies results for the shale reservoir. Integrating these data into the reservoir rock and fluid parameters from simultaneous inversion processing of the 3-D seismic and modeled multi-attribute lithofacies, volumetric and other key determinants (incl. TOC), results in extrapolation and mapping of these characteristics across the whole reservoir for sweet spot delineation