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WELL LOGS AND ROCK PHYSICS IN SEISMIC RESERVOIR CHARACTERIZATION

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Rock Solid Images

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Abstract
Seismic Reservoir Characterization, also known as reservoir geophysics, has evolved over the past several years into a multi-disciplinary, business-critical function in most ED&P organizations. Sheriff defines reservoir geophysics as "The use of geophysical methods to assist in delineating or describing a reservoir or monitoring the changes in a reservoir as it is produced." Reservoir geophysics is applied across a wide spectrum of the oilfield life cycle from discovery and early development to tertiary recovery. One critical part of this process is careful analysis and understanding of petrophysical properties from well logs and core data (seismic petrophysics).

The purpose of this paper is to illustrate why seismic petrophysics is so important and to show how carefully constructed synthetic models can help the geoscientist interpret acoustic and elastic impedance inversion from seismic data.

Introduction

Well logs are sometimes viewed by geophysicists as "hard data" and not subjected to the same level of scrutiny as the seismic data. This can be a mistake because well logs are susceptible to errors from a number of sources. In this presentation we will examine some of the processes and procedures that allow well logs to be correctly used in Seismic Reservoir Characterization. The basic steps in seismic petrophysics analysis are:

- Collect and organize input data
- Perform geophysical log interpretation for volume minerals, porosity, and fluids
- Determine fluid properties (oil API, brine salinity, etc.) and reservoir pressure-temperature
- Perturb reservoir properties using rock physics effective medium models (pseudo-well modeling)
- Compute synthetic seismic traces
- Generate trend curves and crossplots
- Create graphics and digital output files.

Geophysical Well Log Analysis

Well log analysis for geophysics differs in several important ways from standard log analysis. In most cases well logs are obtained for the purpose of estimating recoverable hydrocarbon volumes. Therefore the zone of interest is mainly the producing interval(s). For geophysics, well logs form the basis for relating seismic properties to the reservoir. While we are still concerned about producing intervals, we also need good information about all of the rock through which the seismic waves have passed. Therefore our zone of interest is much larger and encompasses basically everything from the surface to total depth.

In all cases the log data will require some editing, normalization, and interpretation before they can be used in a reservoir study. Several specific analysis steps will be followed:

- De-spike and filter to remove or correct anomalous data points
- Normalize logs from all of the selected wells to determine the appropriate ranges and cutoffs for porosity, clay content, water resistivity, etc.
- Compute the volumetric curves such as total porosity, Vclay, and Sw

- Calibrate the volumetric curves to core data if available
- Correct sonic and density logs for mud filtrate invasion if needed
- Compute Vshear on all wells.

Missing log curves can often be computed with a reasonable degree of certainty. There are two major ways this is done. The first is through application of modern rock physics principles. For example, several deterministic methods exist for obtaining density from sonic logs or sonic logs from resistivity. The other approach is to use neural network technology. This is often required when no direct physical relationship is available.

Well Log Repair

Many, if not most, original well logs require editing and correction before they are suitable for creating synthetic seismograms. The main reasons are:

- Wellbore washouts, casing points, etc
- Mud filtrate invasion
- Gaps, or missing data
- Insufficient log suites.

In these cases, a combination of theoretical, empirical, and heuristic models can be applied to attempt to repair the bad or missing data. A common example is the problem of mud filtrate invasion (Walls, *et al*., 2001; Vasquez, *et al*., 2004). Mud filtrate invasion occurs during drilling with over-balanced mud weight conditions. The positive pressure gradient between the wellbore and the formation causes some of the mud liquids to penetrate into the permeable zones, displacing original fluids near the borehole wall.

The severity of this condition varies greatly depending on permeability, mud weight, mud type, and original fluid saturation. The implications for reservoir geophysics are primarily related to the density log and sonic logs. These two logs sample rock properties close the the borehole wall. Figure 1 is a schematic diagram showing approximate depth of investigation for several common logging tools. Notice that density and monopole sonic are likely sampling the invaded zone. The invaded zone in this example will have higher water saturation than the un-invaded gas sand reservoir. If synthetic seismograms are made from the un-corrected sonic and density logs, the results will not match the seismic data.

This condition can be easily corrected by performing Biot-Gassmann fluid substitution on the measure log curves. The saturation conditions near the wellbore and in the virgin formation can be computed from the shallow and deep resistivity logs, respectively. Figure 2 shows the original and corrected density and sonic curves for a well with water-base mud invasion in gas sand. Figure 3 shows the effect of the correction on the synthetic seismogram from the well.

Rock Physics Modeling and Perturbations

Rock physics modeling can help us understand the behavior of the reservoir and non-reservoir zones and correct for some of the problems encountered in well log data (Avseth, *et al.*, 2001). It is the process of finding a rock physics model that is consistent with the available well and core data. For example, we may find that some zones in the well are closely fitted with an unconsolidated sand model (Dvorkin and Nur, 1996) while other zones follow a cemented sand model (Dvorkin, *et al*., 1994) or elliptical crack model (Kuster and Toksoz, 1974). These models may have adjustable parameters such as pore aspect ratio or critical porosity that can be determined empirically from the local data. Similarly some Vs prediction methods are best calibrated to local conditions if core Vp and Vs data or dipole shear wave logs are available. Rock physics calibrations can also aid in selecting a fluid mixture model such as homogeneous or patchy distribution (Dvorkin, et al., 1999). Well log data should also be compared to available lab data, for example Han, et al (1986) and to theoretical limits such as Voigt (1928) and Reuss (1929) bounds.

One purpose of rock physics modeling is to allow reliable prediction and perturbation of seismic response with changes in reservoir conditions. For example, the data in Figure 4 shows P-wave impedance plotted versus total porosity for a well log from Alaska. Superimposed on the data is a set of rock physics models with different clay fractions. Figure 5 shows that there is a definite link between clay content, water saturation (Sw), and porosity in the reservoir zone. Therefore, if we wish to change porosity, then clay content and Sw must also be changed. The rock physics model allows for prediction of seismic properties away from the wellbore.

Figure 6 shows the results of porosity perturbation over the reservoir interval in the Alaska well. The goal was to create a “pseudo-well” where the oil sand was replaced by wet sand. The original reservoir sand interval (oil filled) has been perturbed by decreasing porosity, increasing Vclay, and increasing water saturation to 100% as determined by the petrophysical relations shown in Figure 5. The resulting acoustic impedance curve in Figure 6 shows little change. However, the Poisson’s ratio for the perturbed (wet sand) interval increases substantially.

Synthetic seismograms were computed for the original (Figure 7) and perturbed well conditions (Figure 8). A zero phase, 15 hertz Ricker wavelet was used. From the synthetic gathers, a stacked trace was computed. Acoustic and elastic impedance inversion was computed on the synthetic traces. Figure 7 shows that for the original well conditions, there are P-wave impedance and Poisson's ratio anomalies in the inverted data. Figure 8 shows the same results for the perturbed reservoir conditions, where porosity is less and Vclay is greater than original. In this case the P-wave impedance anomaly is about the same as original, but the Poisson's ratio anomaly is much smaller.

The reflectivity versus offset was computed for original and perturbed reservoir conditions (Figure 9). For original conditions, the amplitude changes from positive to negative (phase reversal) at about 20 degrees offset. In the perturbed well, the amplitude crosses zero at about 40 degrees.

These models allow us to make a much improved interpretation of the acoustic and elastic impedance inversion. For example, we can say with certainty that acoustic impedance inversion alone will not be enough to discriminate oil from wet sand. However, negative seismic Poisson's ratio anomalies will be indicative of oil saturation, while the wet sand will have almost no Poisson's ratio anomaly.

Effects of Production History

In time-lapse or "4D" seismic projects, the objective is to infer fluid production from two or more seismic surveys recorded at different times in the reservoirs production life cycle. Figure 10 illustrates that multiple wells logs and seismic surveys may have all been recorded at different times. Therefore, in order to get the best well to seismic tie, some wells may need to be moved forward in time (production history) and others may need to be moved backward in time, depending on when they were drilled in relation to when each seismic survey was shot.

Rock physics modeling allows us to make these "time shifts" by changing saturation, pore pressure, and even porosity in the key reservoir intervals. The resulting changes in Vp, Vs, and density can then be used to created synthetic seismograms that correspond to each seismic survey. Further, seismic differences can be computed to allow us to make quantitative predictions of changes in the reservoir (Figure 11).

Even when there is only one seismic survey, wells logs may need correcting for production effects. Referring to Figure 10, consider the situation where Wells 1 and 2 were drilled prior to the recording of seismic survey one, and well 3 was drilled after survey one was recorded. If all of these wells penetrate the producing zones, then changes in pressure and saturation will have occurred during the intervening time. Left uncorrected these changes may cause well to seismic miss-ties.

Summary

The primary benefits of seismic petrophysics are improved well-to-seismic ties, improved calibration of seismic attributes to reservoir properties, and more reliable models of seismic response due to reservoir changes (vertically laterally, and temporally). These models can improve interpretation of 3D seismic data, especially acoustic and elastic impedance inversion. This improved interpretation can reduce drilling risk, enhance field productivity, and ultimately increase asset value.

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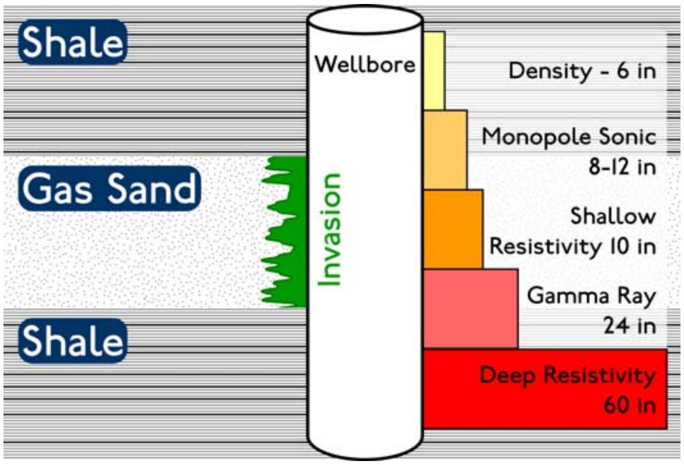

Figure 1: As a result of water-base mud invasion, the logs used to make synthetic seismograms (sonic and density) may be seeing "wetter" rock than the seismic wave.

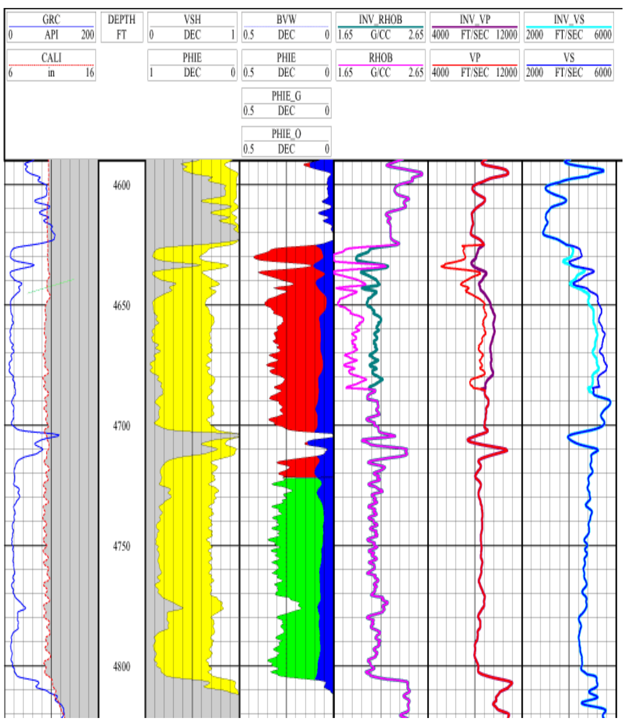

Figure 2: Original and corrected sonic and density logs in a well with water-base mud invasion in a gas sand.

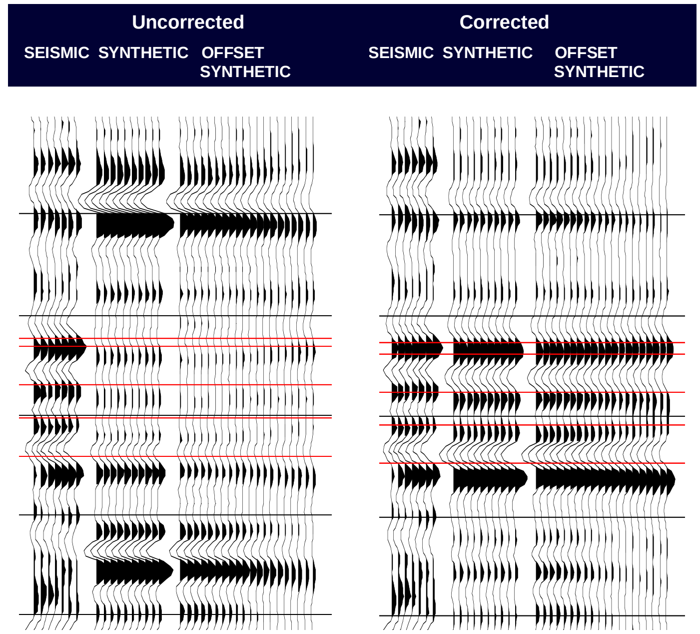

Figure 3: Original (left) and corrected (right) synthetic seismograms in a well with water-base mud invasion in a gas sand. First group of traces are stacked seismic near the wellbore. Second group is stacked synthetic traces. Third group is synthetic gather.

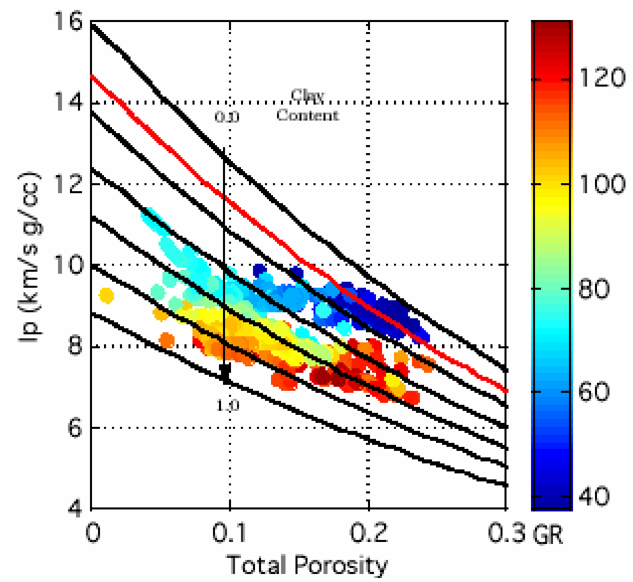

Figure 4: Predicted and measured P-wave impedance versus porosity.

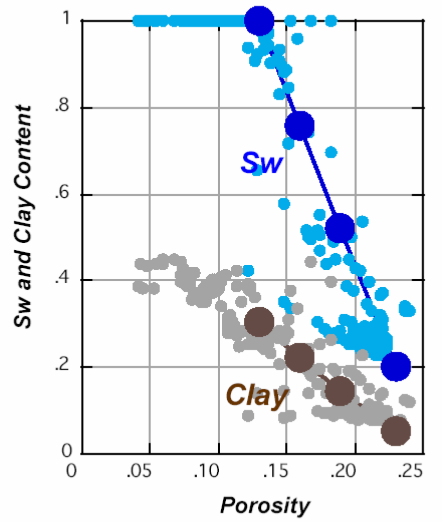

Figure 5: Relationship between water saturation, Vclay, and total porosity for pay sand interval.

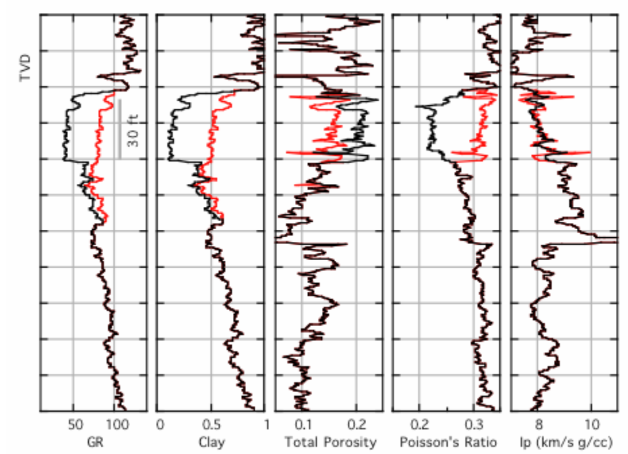

Figure 6: Results of porosity and Vclay perturbation over the reservoir sand interval (black is original data, red is perturbed data).

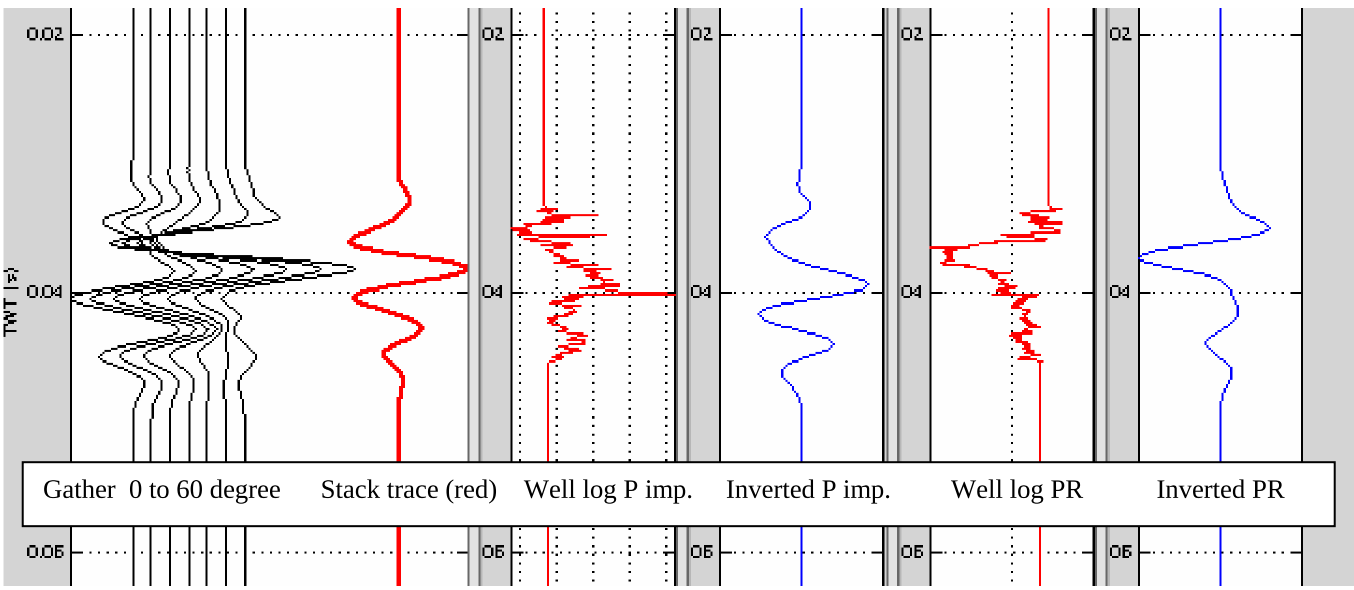

Figure 7: Original reservoir conditions: Synthetic traces, well log impedance, inverted impedance (from stacked trace), well log Poisson's ratio, and inverted Poisson's ratio (from gather).

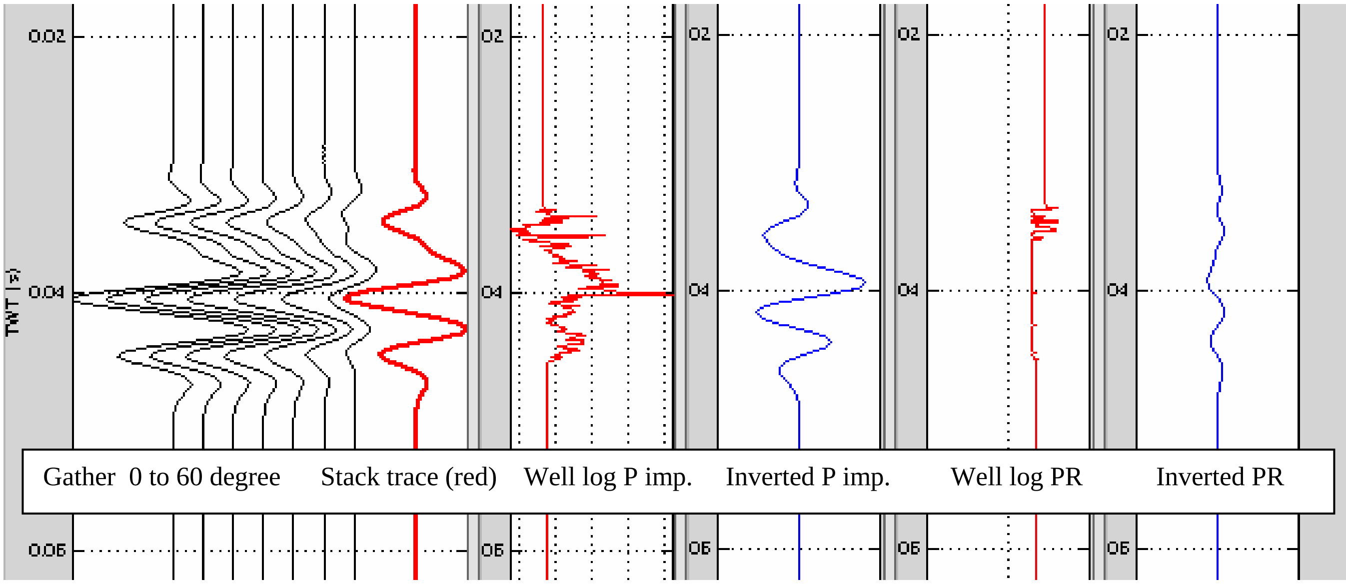

Figure 8: Perturbed reservoir conditions: Synthetic traces, well log impedance, inverted impedance (from stacked trace), well log Poisson's ratio, and inverted Poisson's ratio (from gather).

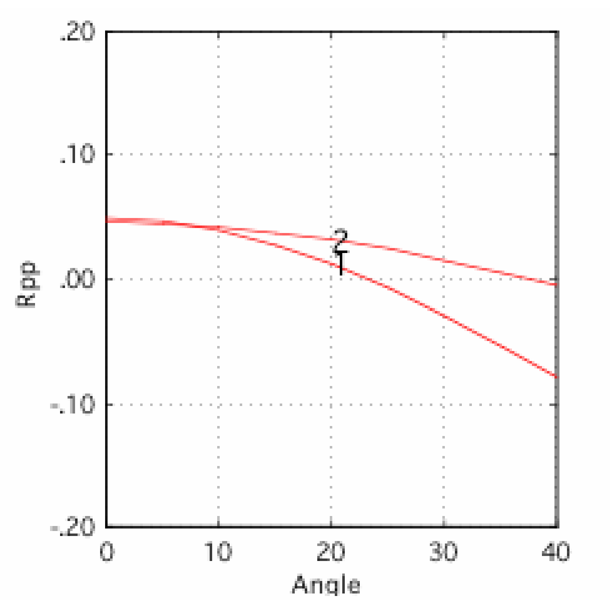

Figure 9: Reflectivity versus angle of incidence for original well (1) and perturbed reservoir conditions (2).

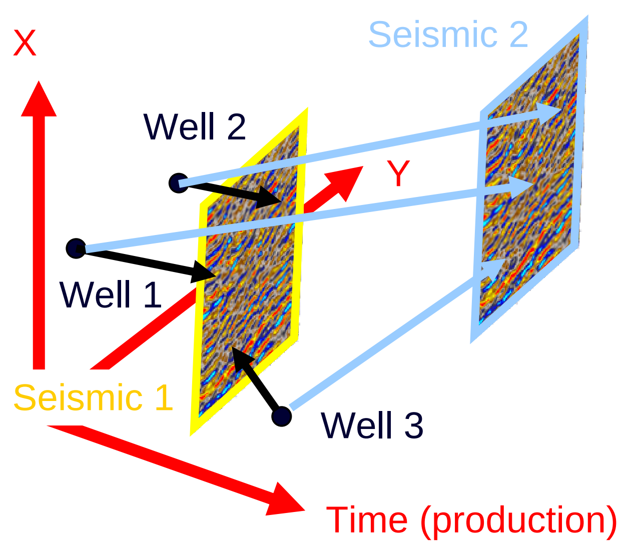

Figure 10: Schematic diagram showing differences in recording time and production history between three wells and two seismic surveys.

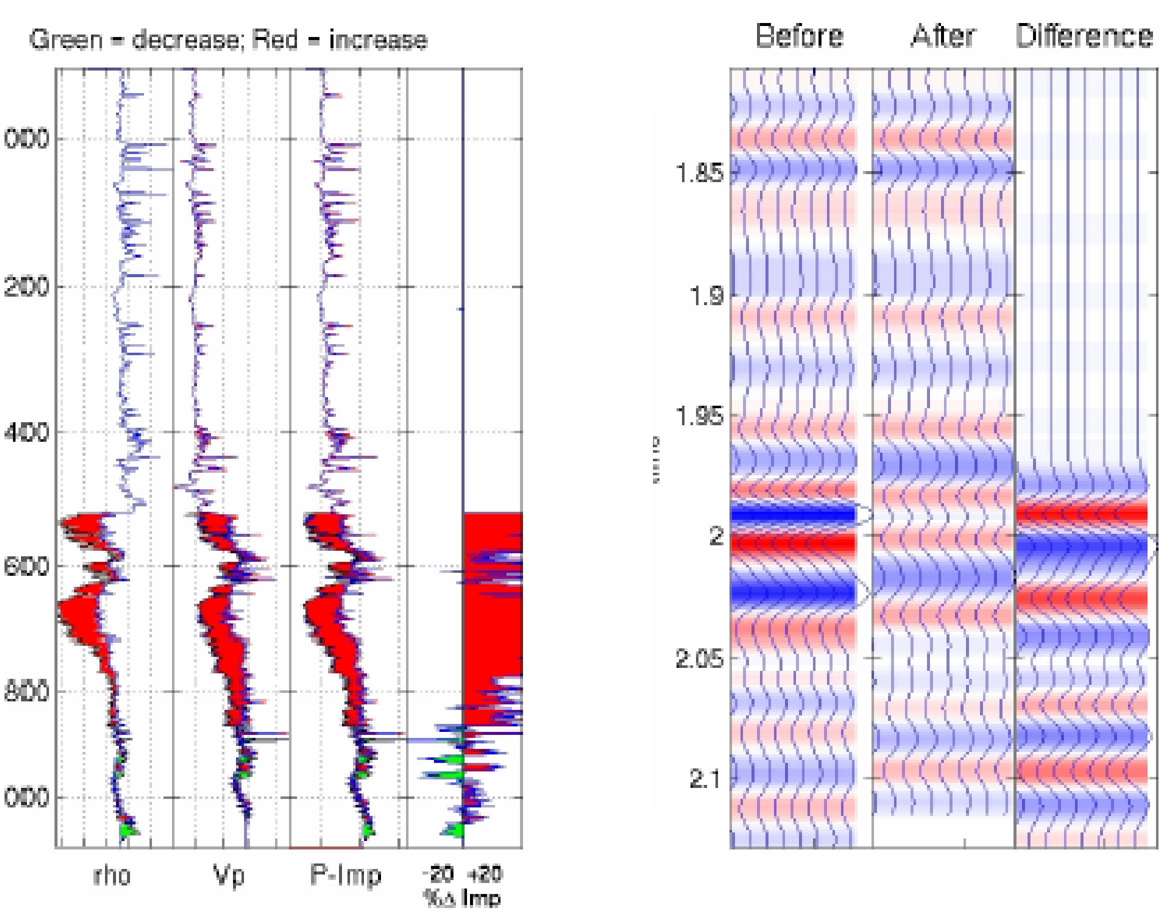

Figure 11: Changes in density (rho), Vp, P-wave impedance, and synthetic seismograms caused by reservoir depletion.