Rock-physics-assisted well-tie analysis for structural interpretation and seismic inversion

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Abstract

Well-tie analysis is a starting point for mapping facies and geology observed at well locations into seismic volumes. This step is very important for any analysis that uses seismic and well data together and can secure more accurate results by increasing consistency between seismic and well-log data. A high-quality well tie is normally considered as the art of an interpreter and is usually practiced through the stretch and squeeze of the synthetics log. Many factors can affect the quality of a well tie, and well-log quality is one of the more important ones. However, interpreters and geophysicists focus mainly on seismic and wavelet components, assuming the well logs are hard data. In practice, well logs are susceptible to different types of errors, which may not be fully addressed during petrophysical work. Rock physics acts as an efficient tool for repairing well logs to achieve a better quality well tie. Examples from various studies are presented to show the importance of further improving well logs using an appropriate rock-physics model before well-tie analysis.

Introduction

Seismic data are widely used for interpreting subsurface structures in both the exploration and production phases during the life of a hydrocarbon reservoir. These interpreted structures provide a framework for interpreting and populating reservoir properties using reservoir characterization methods such as inversion. This requires integration between 1D measurements of the subsurface (well logs) and their 2D and/or 3D images (seismic data) in such a way that both techniques are consistent and can share information with each other. Any workflow in this scope should start by identifying geologic structures from well logs (measured in depth) on seismic data (measured in time). Therefore, we need to convert either well-log data from depth to time or seismic volumes from time to depth in order to make such a two-way conversion link. This link is referred to as the time-depth relationship and is the first and essential step in any project using seismic as an exploration tool. There are many techniques for establishing the time-depth relationship such as using sonic logs, check shots, or vertical seismic profiling (VSP). In practice, a combination of any of these techniques secures improved results. However, in the absence of any of these data, stacking velocities that are derived from seismic data can be used as the last resort, although these velocities can give a poor match compared with other techniques such as sonic logs. Later, this derived time-depth relationship needs to be confirmed through a process known as well-tie analysis, where depth and time measurements are matched with each other, wavelets are estimated, and synthetic seismograms are generated. The difference between the well log and seismic is not only in their domains (depth and time) but also in their sampling rates, which are orders of magnitude different.

Well-tie analysis is a procedure that confirms consistency between well logs and seismic data at well locations by achieving good correlation between seismic data in time and log data in depth. This helps identify sought-after horizons from the well logs as reflection events on the seismic and forms the foundation for structural interpretation, geologic modeling, and advanced seismic characterization methods such as seismic inversion. In general, well-tie analysis is considered as the interpreter's art of generating the detailed waveform and amplitude of the reflectors from interpreted lithology using elastic logs at the well of interest. Therefore, a good well tie depends primarily on the quality of the well log and seismic data and secondarily on the extracted wavelet (phase and amplitude). The impedance logs (from sonic and density) should be filtered by a seismic wavelet in order to tie the well to the seismic data, and therefore, such a wavelet should be extracted from both well logs and seismic data (Ziolkowski et al., 1998). The key seismic elements are first the bandwidth and then the signal-to-noise ratio and duration of the data available for making the tie (White and Simm, 2003), while a much wider group of factors affects the well logs. This can also help us consider further improvements to the applied seismic conditioning workflow to make our seismic data more suitable for interpretation and inversion workflows. However, this paper focuses mainly on the well-log factors and how rock physics can help with an improved model for well logs, leading to improvements in the well-tie analysis. This in turn can result in better estimation of a wavelet, a more accurate structural framework, and improved results for seismic characterization methods.

In practice, well-tie analysis computes reflectivity from velocity and density, converts it from depth to time, and convolves it with an estimated wavelet to generate a synthetic trace. Finally, the goodness of fit between synthetic and seismic trace is increased through an iterative process known as "stretch and squeeze" to achieve a high crosscorrelation between both traces. This means that the time-depth relationship will be updated, as this process focuses more on the timing errors than the amplitude errors. The tie is considered accurate enough when filtered reflectivities through the seismic wavelet at the well location are highly correlated to the seismic data. Here, we need to distinguish between goodness of fit and the accuracy of the well tie because higher goodness of fit does not always imply higher accuracy. It is now well known that sonic and seismic velocities can have a different frequency-dependent dispersion effect (Jarvis, 2006), and stretching the synthetic seismic can compensate for this by extending the depth over more time (reducing sonic velocity). Applying stretch and squeeze to compensate for other problems with sonic and density logs seems unscientific and definitely not good practice (White and Simm, 2003). The reason for this is that if we replace bad data with a poor estimate, we may not have done much good with respect to the cumulative error and may add false

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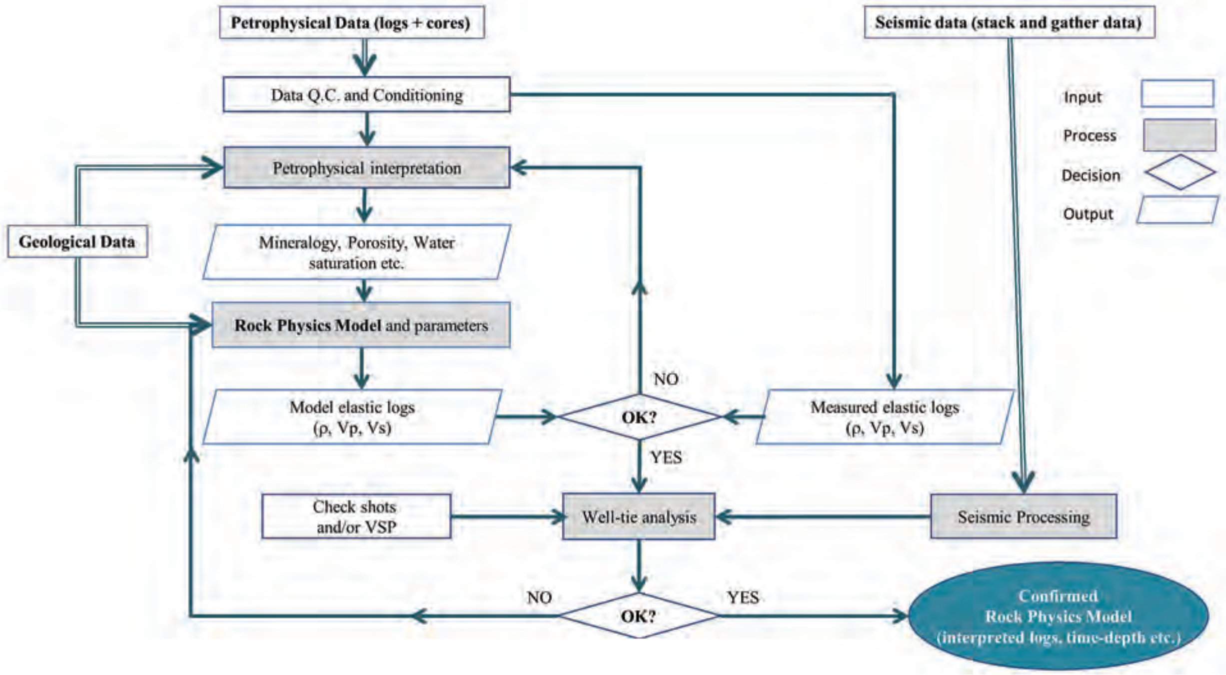

Figure 1. A rock-physics-based workflow consisting of petrophysics (rock physics and rock-physics well-tie elements) to improve the correlation between synthetic and seismic by updating the well log through a rock-physics model.

reflectivities (Burch, 2002). Well-log data, which are the starting point of any well-tie analysis, may sometimes be of poor quality and/or inconsistent with other surrounding wells and/or even have some data missing. Therefore, well-log conditioning and rock-physics modeling need to be applied prior to well-tie analysis, and the results should improve the quality of the well tie (Sams, 2014). Figure 1 depicts an integrated workflow that includes petrophysics, rock physics, and well-tie analysis. This workflow can sufficiently address the problems with well logs and improve well tie by reviewing and revising well-log interpretation using rock-physics modeling techniques. It starts by building a rock-physics model based on petrophysical and geologic data, and its inputs from petrophysics as well as rock-physics model parameters are updated in an iterative approach. Lastly, the results are checked using both petrophysics and seismic data. The outcome of this process is a confirmed rock-physics model with the outputs validated in both the petrophysical and seismic domains. The inputs to this model (well logs, time-depth relationship, etc.) are improved accordingly based on the output validation.

This workflow is also known as seismic petrophysics, in which petrophysical interpreted logs are modeled using rock physics. The final quality control on the modeled logs is performed by well-tie analysis in which improved well tie is achieved. In the following sections of this paper, this integrated workflow is discussed in depth with different real data examples.

Rock-physics modeling and seismic petrophysics workflow

Seismic reservoir characterization is a well-known technique for helping to describe reservoir properties through careful analysis of petrophysical and seismic data. It requires integration between these two disciplines in such a way that petrophysics and seismic data are consistent and can provide input/output for each other. The role of petrophysics is to accurately compute the volumes of fluids (such as hydrocarbons) and lithologies (such as different minerals), which will be used later as inputs to our rock-physics model. These interpreted well logs are normally used to understand the relationship between reservoir properties and seismic through synthetics generated using sonic and density logs. The convolutional model for generating synthetic seismic data parameterizes the subsurface by its density and velocities. In this regard, sonic and density logs from petrophysical studies are considered the main source for such parameterization and are used quite frequently by geophysicists to link reservoir properties and seismic traces at the well locations. However, the validity of this link depends primarily on the validity of sonic and density logs. These two logs are sometimes assumed by geophysicists as hard data (Walls et al., 2004) compared with seismic data. It is important to note that log data, in general, are exposed to different sources of errors, which could make the final link between reservoir properties and seismic totally erroneous. These errors could come either from raw logs during measurements and/or their processing and interpretation.

In general, the well-log measurements are subject to various sources of errors such as the quality and availability of the measured data. The common problems with well-log data include:

- Wellbore environment problems (e.g., washouts, mud filtrate invasion, spiral holes, borehole size, mud type and weight, etc.)
- Anomalous data points (e.g., sonic cycle skips)
- Insufficient log suites (e.g., no S-sonic logs)
- Gaps or missing data (e.g., between two different logging runs)
- Tool pulls, depth matching errors
- Digitizing errors and inconsistencies between log suites due to service company, tool type, and even petrophysical interpretation methods

These problems are common for all well-log types, and petrophysical approaches deal with them through editing, calibration, and conditioning. The procedure to address these factors has been discussed by many authors (e.g., Ziolkowski et al., 1998; White and Simm, 2003), and the techniques are implemented during everyday practice of petrophysical work. In addition, sonic logs are biased by their own specific issues mainly relating to how a signal is generated, propagated, and received. The errors can include logging noise (i.e., high-frequency noise generated by tool movement along the borehole), electrical signal noise (i.e., a false first arrival due to a malfunction of the electronics), cycle skipping (i.e., the first arrival is missed by the receiver and a later event is detected), measurement scale differences (i.e., different measured frequencies), and anisotropy (i.e., intrinsic or extrinsic geologic features which make velocity direction dependent). The latter issues are mainly concerned with how the sonic waveforms propagate in the formation close to a borehole where in-situ conditions (the conditions seen by the seismic wave) are changed by drilling operations. Some of these problems are already addressed through the invention of new tools and by calibrating them with check shot or VSP data. However, these calibrated sonic logs may still not be quite correct and bias well ties toward the wrong layer properties. One effective approach for confirming and correcting sonic and density logs is rock-physics modeling, which has not been considered in many studies.

Rock physics provides a set of relationships that bridge the gap between reservoir and elastic properties. These relationships are also referred to as petroelastic models and attempt to define how reservoir properties (e.g., porosity, saturation, etc.) and reservoir architecture (e.g., laminations, fractures, etc.) influence elastic properties (e.g., V_P/V_S elastics, etc.) and vice versa. They should allow for a reliable prediction and perturbation of the seismic response with changes in reservoir conditions (Saberi, 2013). Rock physics can therefore be considered as a quantitative tool for addressing different well-log issues by understanding rock behavior under different conditions and then modeling it. This approach is normally referred to as seismic petrophysics and is used to address some of the existing issues with petrophysical logs and their interpretation (e.g., Smith, 2011; Sams and Focht, 2013). The results of this process are expected to mitigate well-log errors, which should in turn decrease data scatter and increase the separation between different facies in a crossplot analysis. Figure 2 shows an example of the output of the seismic petrophysics workflow on a well, making petrophysical and seismic data consistent and resulting in a better facies separation by removing possible logging errors (Jarvis, 2006).

Seismic petrophysics normally begins with the evaluation of well-log data performed by using some theoretical limits such as Voigt (1890) and Reuss (1929), bounds, or even available empirical models for the same geologic settings. The source of the abnormal data should be recognized and treated accordingly. This is normally followed by the building of a predictive and consistent rock-physics model for the intervals with complete and good-quality data. The inputs from petrophysics and/or core data at those intervals will define the model and can be used to calibrate its parameters (such as pore aspect ratio, critical porosity, etc.). These parameters should then be extended to the whole length of the wellbore, considering the condition of the wellbore and the geology. This is an iterative approach in which both inputs and outputs are updated to achieve an acceptable consistency through the selected rock-physics model (Saberi, 2017). The primary benefits of seismic petrophysics are improved petrophysical interpretation, better well-to-seismic ties, and improved calibration of seismic attributes to reservoir properties and their changes. The potential operational benefits are reduced drilling risk, enhanced field productivity, and ultimately increased asset value. In the next section, different examples are presented to show the value of rock-physics-corrected well logs to achieve a higher well-tie quality.

Examples of rock-physics-assisted well-tie analysis

Seismic petrophysics can be a robust tool for correcting elastic logs because it finds the underlying reason for the poor well tie and models well logs based on the actual subsurface rock microstructure to achieve a geologically plausible correction. In addition, the modeled well logs should be confirmed through the well-tie analysis procedure to assure that what is "seen" by the well logs is consistent with what is "seen" by the seismic. This section presents case studies dealing with different well-log problems and shows how rock physics can help achieve a better well tie.

The first two examples show the effects of invasion zones on well-tie analysis. This is a very common problem in well logging. Invaded zones are defined as zones around the wellbore in which mud filtrate replaces in-situ fluid. Sonic and density tools have shallow depths of investigation so intervals that have been badly affected by invasion will lead to erroneous measurements. Log

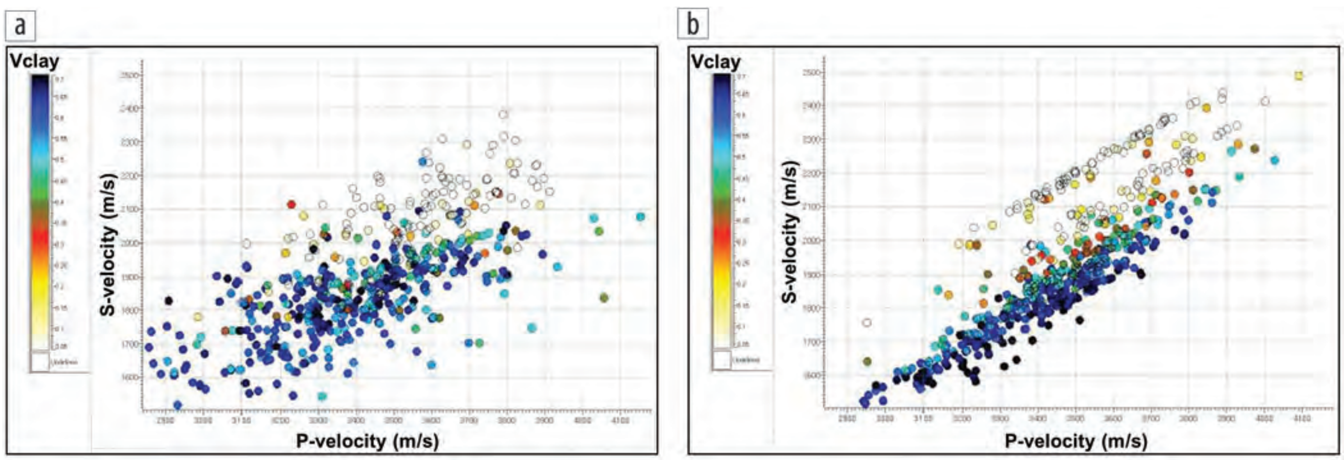

Figure 2. Two crossplots for P-wave velocity versus S-wave velocity using well logs. (a) Generated before implementing the seismic petrophysics workflow. (b) The reduction in scatter after the seismic petrophysics workflow. Modified after Jarvis (2006).

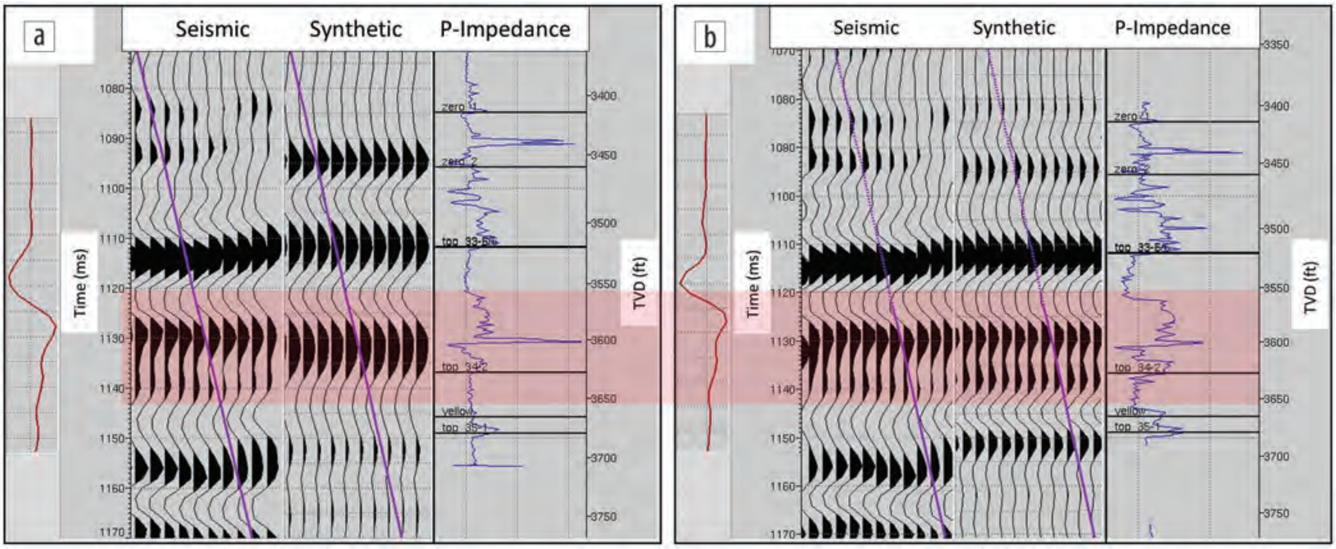

Figure 3. An example of (a) the invasion effect on well-tie analysis and synthetics generation and (b) correcting invaded zones with a better match for well-tie analysis. The red band shows the interval affected by this correction and how synthetic response is improved. Also note the small changes of new wavelet for modeled logs presented on the left side of both images.

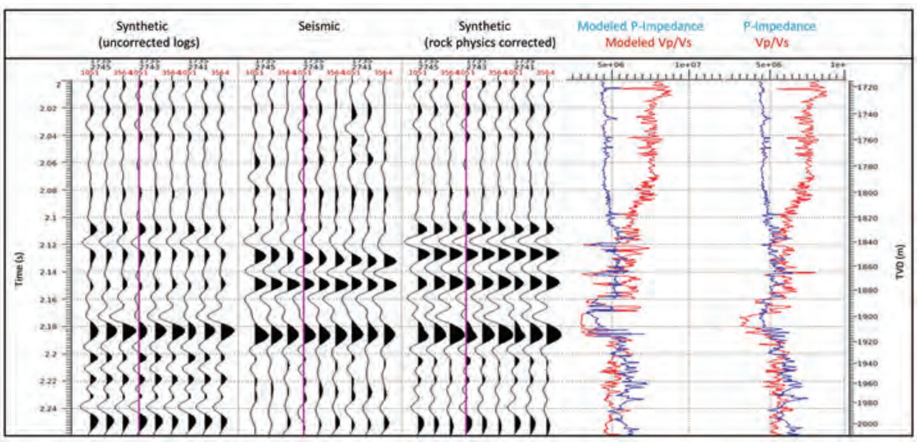

Figure 4. Correcting elastic logs for invasion effects. P-impedance, V_P/V_S logs, and synthetics are shown before and after (modeled logs) invasion correction. These synthetics are compared with the measured seismic (second track from left). Modified after Zeb and Murrell (2015).

correction for invasion is a complicated process as the invasion profile is uncertain and there may be variations between wells due to drilling mud, logging time, porosity, permeability, etc. Figures 3 and 4 show how invasion can lead to a poor well tie and how rock-physics modeling can improve the quality of the well ties. In Figure 3, the invasion effect has been corrected by using an inclusion-based rock-physics model, resulting in a better quality well tie and a higher crosscorrelation between seismic and synthetic seismic. Here, the estimated wavelet is also slightly improved, which can have a positive impact on the quality of structural and inversion results. This rock-physics model uses different pore aspect ratios for sand and shale, representing their different pore geometry.

Figure 4 shows another example from Zeb and Murrell (2015) of the role of seismic petrophysics in correcting well logs to improve well-tie quality. A clear improvement can be observed after the removal of invasion effects from elastic logs.

Another common problem in acoustic logs is cycle skipping. The acoustic wave generated by the sonic tool is attenuated as it is propagated through the formation and borehole environment. If this attenuation weakens the signal sufficiently, the sonic receiver misses the first arrival and detects the next signal relating to the next event, and an anomalously high transit time (spike) will be recorded. This can happen in unconsolidated or fractured formations where generated and/or received signal is poor. Cycle skipping can be easily recognized from its spiky signature. The normal practice of arbitrarily despiking the logs is not recommended as certain geologic features (e.g., calcite stringers) can cause genuine spikes. A more rigorous approach is to use an appropriate rock-physics model to replace the spikes.

Figure 5 shows an example of a poor-quality well log due to four different causes (labeled on the figure) including cycle skipping, missing data, washout zone, and invasion which resulted in a poor well tie. The first problem is caused by cycle skipping, which can be observed on the synthetic traces as high-amplitude events. The second problem is caused by incorrectly interpolated missing log data (due to different reasons such as a change in the logging run). The third issue relates to a washout zone (anomalously enlarged borehole diameter), which can be due to different factors relating to geology or drilling operations. These regions will cause incorrect readings for logging tools and are normally treated during petrophysical processing. Figure 5 shows how these zones can distort the synthetic seismic and affect the well-tie analysis and wavelet estimation. It clearly shows that the rock-physics toolbox can replace the erroneous log data to improve both the wavelet estimation and well tie. The new estimated wavelet (Figure 5b) contains higher frequencies, which in turn will support structural interpretation and inversion workflows with more information. Here, petrophysical results are updated in an iterative manner using the Xu and White model (Saberi, 2017) based on the modeling error observation.

Anisotropy and scale effects are other important factors to consider when linking well logs to seismic. Sedimentary rocks are composed of layers, which can exhibit a range of dips and thicknesses. Both characteristics can affect the quality of the measured sonic logs and their link with seismic due to anisotropy and different sampling rates for each measurement. Figure 6 shows a synthetic data set of thin subseismic-resolution horizontal layers and relevant synthetics for sampling at a well-log scale and sampling at a seismic scale. The "log synthetic" shown in Figure 6a is generated using the original impedance log (thin layers). In Figure 6b, the P-impedance well log is first upscaled to seismic frequency using the Backus (1962) model and the "seismic

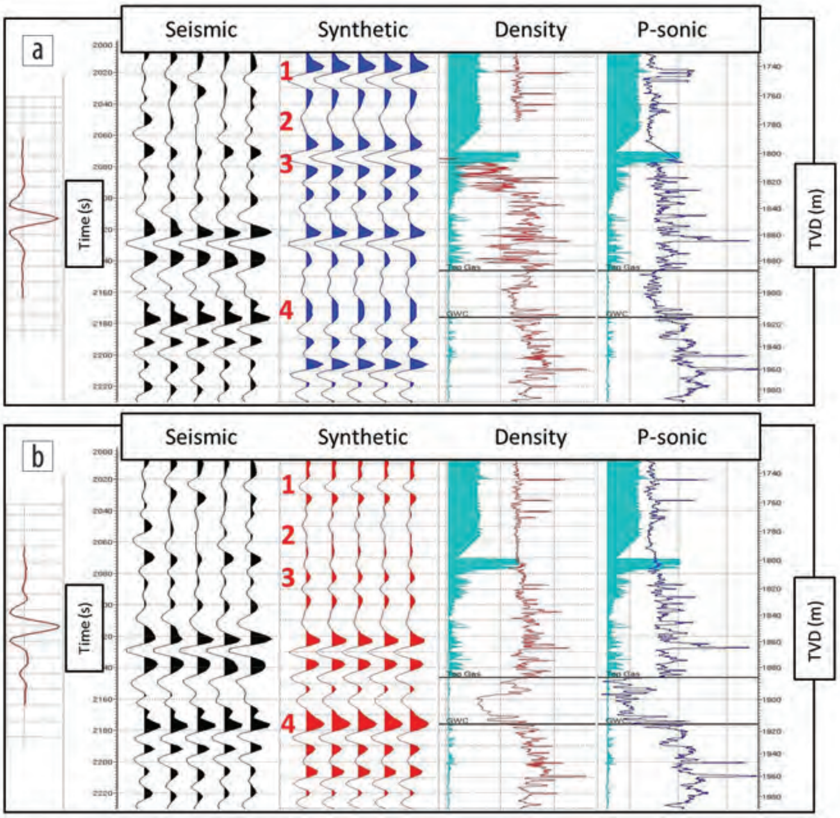

Figure 5. Well-tie analysis using (a) initial sonic and density and (b) modeled sonic and density. Initial logs are affected by four different sources of errors: cycle skipping, missing data, washout, and invasion zone, numbered 1 to 4, respectively. The green-filled curve shows the differential caliper log. Modified after Sidi and Duncan (2007).

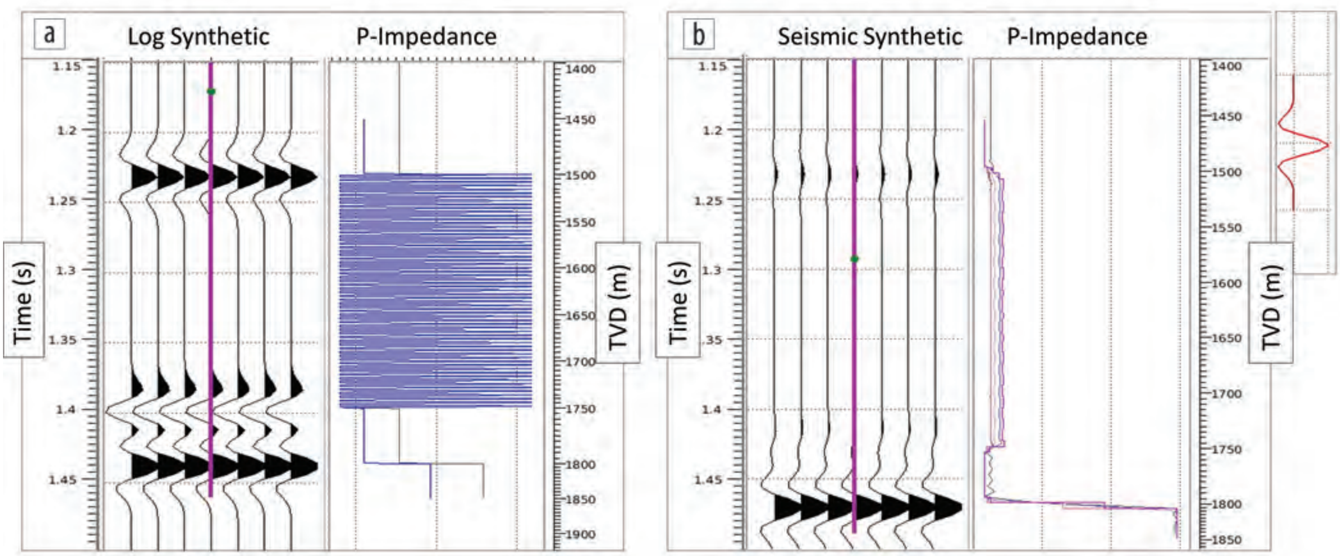

Figure 6. A synthetic data set to generate seismic for (a) very thin layering as observed at the well-log measurement scale and (b) upscaled using the Backus (1962) average at 125 Hz frequency, as would be observed at the seismic measurement scale. It can be seen that seismic shows a lower velocity at (b), which results in a stretch of the seismic traces.

synthetic" is then generated. Clearly, these two scenarios generate different seismic responses with a lower interval velocity for the latter case in Figure 6b. This experiment shows the necessity of upscaling the well log to the seismic frequency before performing a well tie, especially in thinly layered formations.

Figure 7 shows the last example from Hornby et al. (2003) on how anisotropy leads to a poor-quality well tie in deviated wells. Anisotropy is defined as the directional dependency of velocities. In the case of a layered medium like a sedimentary rock, a change in the direction of wave propagation with respect to layering will affect measured velocities (Saberi and Ting, 2016). This effect is more prominent when highly deviated wells (more than 50°) are drilled within sedimentary rocks with obvious layering. In such scenarios, the sonic velocity will have a lower value compared with a vertical measurement in the same formation, and this should be attributed to the well direction and not rock properties. In the case where well logs from highly deviated wells are going to be used in a well-tie analysis along with other wells, then, for the same formation, different velocities will be assigned which will result in poor well ties. Figure 7a shows the volume of shale, well deviation, and measured (black) and anisotropy-corrected (gray) sonic log. Here, the main reason for anisotropy is attributed to the shale volume. The anisotropy correction is made based on this assumption, which has resulted in an improved well tie.

Conclusions

This paper has discussed how different well-log-related problems can affect the quality of well-tie analysis and create a mismatch between synthetics and seismic. These mismatches can result in considerable uncertainty during structural interpretation and reservoir characterization studies. Rock physics can play an intermediate role by integrating and exchanging information between different subsurface disciplines. It can address different well-log-related problems (such as poor or missing data) more effectively than standard petrophysical corrections to improve the match between well-log synthetics and seismic. Different case studies dealing with well-log correction for poor data, invasion interval, washout zone, and anisotropy using a rock-physics modeling technique are presented to show the value of a seismic petrophysics workflow on well-tie analysis. This workflow improves well-log interpretation in petrophysics and should simultaneously address issues relating to poor well-tie quality by improving interpreted logs. TLE

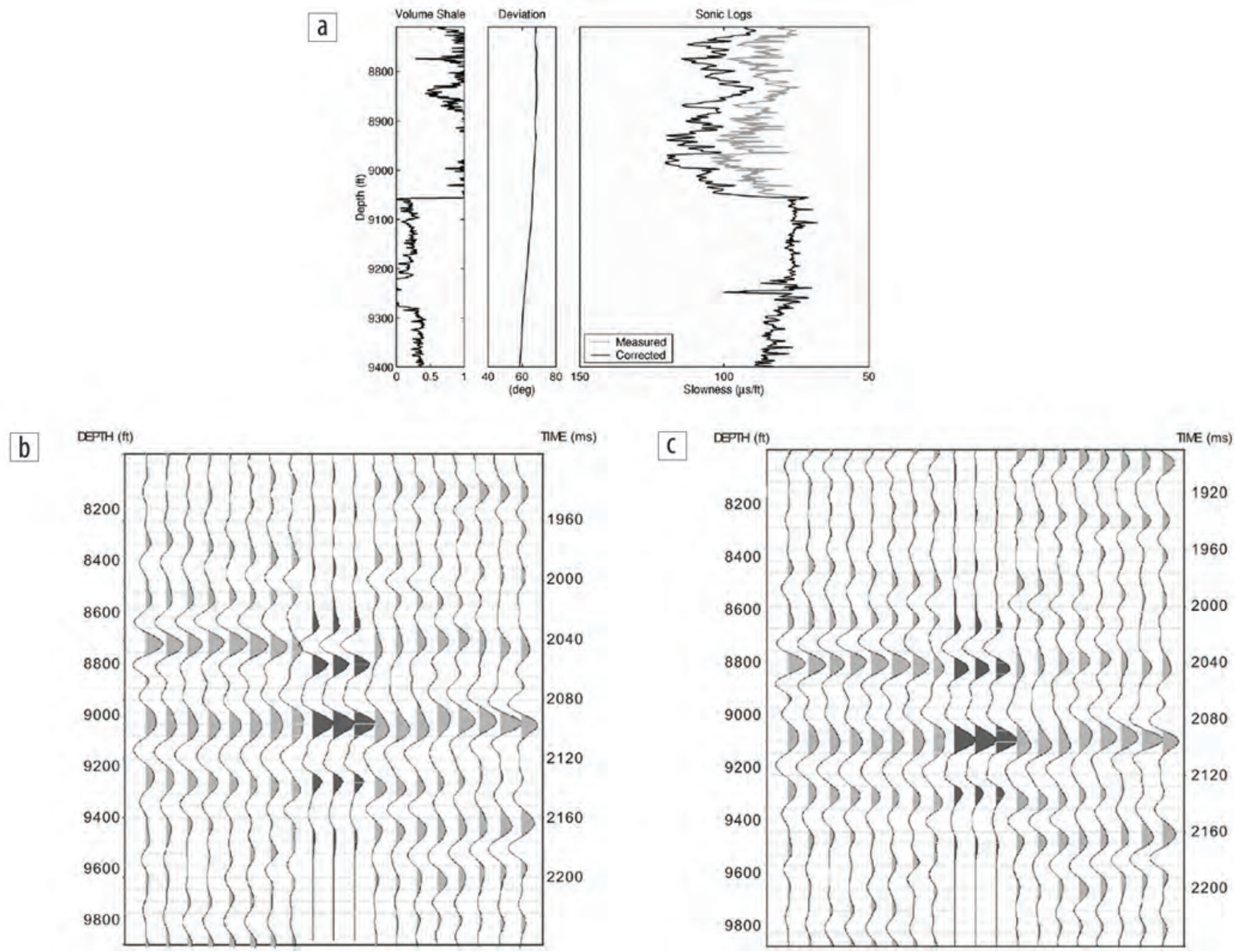

Figure 7. Effects of anisotropy on well-tie analysis. (a) Volume of shale, well deviation, measured sonic (gray) and anisotropy-corrected sonic (black) curves. (b) Comparison between measured seismic (gray traces) and measured sonic (black traces). (c) Comparison between measured seismic (gray traces) and anisotropy-corrected sonic (black traces). Modified after Hornby et al. (2003).

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