Assessing and using seismic amplitude and acoustic impedance uncertainty in Saudi Arabia

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In Saudi Arabia, seismic data have played an indispensable role in exploration and production. The most significant impact has been structure mapping via traveltime information. However, there has also been successful exploitation of amplitude information; e.g., determination of lithology, fractures, and porosity. A desirable goal is to make more use of all of the seismic information, realizing that this goal is complicated by the fact that the seismic data and reservoirs in Saudi Arabia are primarily in challenging land environments.

There are many data quality issues that tend to accompany land data in general (e.g., the weathering layer, ground roll, etc.), and others more specific to the Middle East and Saudi Arabia (dune/sabkha topography, shallow karsting, etc.). Hence, there is justifiable concern regarding the quality of seismic amplitudes and their use impacting exploration and production decisions (e.g., whether or not to incorporate seismic information beyond traveltimes in reservoir model building). One approach is to reduce undesired effects that contaminate the amplitude information (multiples, statics, noise of various kinds, etc.). However, at any given state-of-the-art in land acquisition and processing, we recognize that some of these unwanted effects will remain.

Alternatively, the use of imperfect amplitude information for prospecting and reservoir geophysics can be addressed by attempting, in a quantitative manner, to assess, and account for, in some way, the uncertainty in the amplitude data with regard to subsequent applications. However, we have been unable, so far, to identify any commercial, off-the-shelf technology that seems adequate for this goal. Perhaps this is due to the fact that, for the most part, contractors’ efforts are driven by primary industry needs, and most of the rest of the world deals mainly with higher quality marine data. Hence, their emphasis has been mainly on exploiting amplitude information, under the reasonable assumption that it is reliable. Given this state of affairs, Saudi Aramco has undertaken an internal effort to develop the needed technology.

This article refers to recent progress toward resolving this problem. First, we introduce some issues in defining and quantifying seismic amplitude uncertainty. Then, since one of the common uses of amplitude data in exploration and production is acoustic impedance derived via poststack inversion, we discuss the problem of propagating amplitude uncertainty into an estimate of acoustic impedance uncertainty. Finally, we present some ways in which confidence estimates can be used in exploration and reservoir geophysics in both a qualitative and a quantitative manner using real data examples.

The data examples in this paper come from three diverse areas in terms of near surface problems. In study area A to the west (Figure 1), the near surface is made up of wadis with outcrops of limestone, anhydrites and sandstones on-lapping onto the Arabian Shield. The primary reservoir target is Permian sandstone. In study area B (Figure 2), there are many jebels, sabkhas, and sand gravel plains. In study area C (Figures 3-5), there is karsting, which is normally comprised of sinkholes and caves near or on the surface. In the last two cases, the primary reservoir level is Jurassic carbonate.

Background. Uncertainty analysis is a broad subject in its own right and we need only mention a few essential ideas here. It is important to distinguish between error estimation and error propagation, where we borrow an example from freshman physics lab to illustrate the concept. Consider a student who needs to determine the density of a sphere. She could proceed by measuring the sphere’s diameter with a ruler, and its mass with a weight scale. The volume could be obtained from the diameter using a well-known formula. Finally, the density could be calculated by dividing the mass by the volume.

Figure 1. Two different angle stacks from the same data in area A, with mean SNR estimated over a single time window.

Figure 2. Confidence bounds for an area B well trace from an impedance volume derived from production seismic inversion (blue) overlaid with the filtered Al log (red). This well was used in deriving the wavelet used in inversion and the low frequency trend. The seismic noise estimate was also low in the vicinity of this trace.

In this exercise, two measurements were made and two calculations done. A typical approach to determining the uncertainty in the measurements would be by repeating them and then computing the mean and standard deviation of each, where the latter quantity represents uncertainty due to random errors. We can refer to this step as error estimation. Then, we need to combine these errors into an uncertainty estimate in the final quantity—i.e., density. This latter step is called the
propagation of errors, because it propagates the effects of the errors through the various formulae into a final result.

Below, we refer to the problem of estimating error in various input quantities, which might be the seismic amplitudes, the wavelet, horizon picks, etc., and the additional problem of propagating the errors into a final estimate of uncertainty in some derived quantity—say, acoustic impedance via inversion. These ideas are pertinent for what we term the postinversion approach to uncertainty analysis. We will also discuss an alternative approach, which is to assume a probabilistic model for inversion and obtain the uncertainty estimate as a natural byproduct.

Seismic amplitude uncertainty. In the sense of the discussion above, we would like to have many realizations of a seismic trace, where we can treat each as being sampled from a joint distribution characterizing all of the noise processes, and the expected value of which would be the signal. From these realizations, we could make an estimate of the standard deviation at each time sample. This would constitute what we mean by seismic amplitude uncertainty due to random noise. Since we only have one realization of each stacked trace, this ensemble approach is not directly possible. Hence, indirect approaches have been invented, usually involving the autocorrelation and crosscorrelation functions. This assumes some sort of signal and noise model of the trace, where, typically, the noise is white or colored, and spatially uncorrelated.

This idea is illustrated in Figure 1. An estimate of the noise standard deviation was provided by the zero lag value of the noise autocorrelation function (Dash and Obaidullah, 1970), after proper normalization. The signal standard deviation was obtained in the same manner, and the results are shown in terms of signal-to-noise-ratio (SNR).

We have extended this type of analysis in several ways: (1) time-varying, trace-by-trace, and (2) computation of the full noise covariance matrix (the off-diagonal elements accounting for the noise color). Depending on the signal model, one can also attempt to include spatially correlated noise, which may be a way to incorporate information about multiples. This problem is still under investigation. The resulting covariance matrix corresponding to seismic amplitude noise is a useful quantity in its own right. However, many seismic amplitude applications involve a further transformation to acoustic impedance via poststack seismic inversion.

Acoustic impedance uncertainty. Uncertainty in many different factors will affect the impedance estimate—e.g., time-to-depth conversion of well information, horizon time picks, the well interpolation scheme for the low-frequency trend or start model, wavelet uncertainty, and seismic amplitude noise. Ultimately, the most correct way to address the problem of uncertainty analysis for inversion is to make use of a probabilistic method of inversion (e.g., Bayesian), which is currently under development. However, we have also addressed the postinversion uncertainty analysis problem for two main reasons. First, we have addressed this problem to fill short term needs. The Bayesian approach is not yet ready for production use. Even when it is, many legacy impedance volumes already exist which will not be re-inverted immediately. Secondly, the input covariance matrices for seismic data, wavelet, etc., which are required for the postinversion method, are also required for the probabilistic approach. So, there is no wasted effort.

The postinversion approach uses a transformation derived from conventional error propagation techniques based on a Taylor series analysis. To be somewhat independent of the type of inversion method used, some fairly stringent assumptions have to be made, the principal one being that the inversion method used was of a common type of algorithm based on finding a solution that forward models to match the seismic trace, and that it was run without tight prior model constraints. The Taylor series expression for variance yields an
inverse problem for the acoustic impedance covariance matrix, the use of which is discussed below. The diagonal of the resulting impedance covariance matrix can be used to define confidence bounds such as are illustrated in Figure 2.

Uses. Quantitatively, the acoustic impedance covariance matrix can be used directly in the objective function for reservoir model history matching for one approach to incorporate seismic information. The objective function contains various terms controlling how much perturbation to the reservoir model is allowed in order to match the input data, which can include surface seismic (usually after transformation to acoustic impedance), as well as production data, etc. Covariance matrices associated with each term control the relative weighting and importance of the particular data types in influencing the model.

Alternatively, the diagonal of the impedance covariance matrix can be used to derive weights to selectively control how much influence the AI volume is allowed to influence the geostatistical interpolation of well data (such as porosity) for reservoir model building. Qualitatively, the kind of displays in Figures 3-5 such as SNR, seismic noise, relative and absolute AI uncertainty, can be interpreted visually to assess confidence, and help in making prospecting and drilling decisions.

The future. We need to eventually incorporate multiples and other spatially correlated noise into the seismic covariance matrix, as well as wavelet uncertainty, low frequency trend (start model) uncertainty, etc. However, incorporating all of the effects into the postinversion approach becomes cumbersome. At some point, it will be actually easier to incorporate the various input uncertainties into the Bayesian program and reinvert the data.

All of these efforts are under way and progress is being made. Algorithm development and improvement in geostatistics and history matching are involved as well. For example, we have made some progress on the problem of incorporating uncertainty in secondary information by modifying the current approach to collocated cokriging, and we are also working with the reservoir simulation research group regarding the incorporation of seismic uncertainty information into history matching.


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