An interesting idea that was highlighted at the recently concluded 2015 SEG Convention at New Orleans was about carrying out seismic impedance inversion in the depth domain. ‘Inversion’ refers to the transformation of seismic amplitude data into acoustic impedance data.

Seismic data represent an interface property wherein reflection events are seen due to relative changes in acoustic impedance of adjacent rock layers. Such observed amplitude changes may not indicate if the amplitude changes relate to lithology variations above or below an interface. Acoustic impedance is a physical rock property, given as the product of density and velocity. Well logs measure both these entities directly, so that by dividing the density log with the sonic log, acoustic impedance log is obtained. Thus while acoustic impedance is a layer property, seismic amplitudes are attributes of layer boundaries.

Impedance inversion has been carried out in the time domain for the last four decades. If it has to be carried out in depth, there are a few questions that come to mind — what is so different about carrying out inversion in depth rather than time, how does it help, and if it were important, why did we have to wait for four decades to talk about it now? Let us address each of these questions, taking up the last one first. Why now?

In the last two decades, rapid strides have been made in the development of depth migration algorithms and procedures. We have now reached a stage where post-stack or pre-stack depth migrated volumes are sought whenever the interpretation on seismic time volumes seems inadequate, or does not provide ready answers to some of the questions pertaining to geology.

Besides, the computational effort required for depth imaging is way more than time migration, due to the iterative nature of velocity revisions required in the process. Gradually, as the computational costs have become cheaper, so has the advancements of the algorithms from 2D to 3D, and then from post-stack to pre-stack applications. These days, large data volumes are stored and handled in the memory, which also helps in making the processes run efficiently.

Irrespective of whether the subsurface geology is a simple layer-cake type, or is relatively complex, ideally, what is required from a 3D seismic data volume is a reliable image of the subsurface that mimics the geology. We are aware that the subsurface rocks exist in depth and the wells drilled into these rocks are also measured in depth. But the seismic reflection data are acquired and processed in two-way travel time. Interpretation carried out on seismic data (in time) for stratigraphic objectives such as sequence stratigraphic or seismic facies analysis usually works as it does not change significantly if the structure changes. Structural interpretation when carried out in time is likely to have pitfalls in the form of artificial features. Such features can result from the local topography or the near-surface velocity changes, which can cause lateral changes in the travel-times of the propagating seismic waves. Lateral changes in the overburden such as carbonate buildups can cause velocity pull-ups or push-downs. Similarly, complex structures can easily cause inadequate subsurface illumination and result in poorly-focused reflection events that have amplitude and phase variations. Also, fault termination features could be misaligned. All these pitfalls result in misleading interpretations. Given an accurate velocity-depth model, depth migration overcomes velocity pull-up and push-down effects, enables calculation of more accurate volumetrics, and also improves the vertical and lateral resolution by properly aligning events. But how does this happen?

Depth migration handles better the seismic signal wavefront bending caused by velocity contrasts in the subsurface, and thus repositions the reflection events with greater accuracy. The usual way to carry out depth imaging is to first construct an accurate subsurface velocity model in depth. This requires input from the seismic data, the available borehole data, the interpretation carried out in terms of horizon picking and fault interpretation on the seismic as well as the right workstation software tools to integrate all this information. Another important input is accounting for anisotropy in the subsurface rocks, i.e. variation of seismic velocity with direction of propagation. Shale formations for example exhibit a higher velocity parallel to the bedding direction than in a direction perpendicular to it. Similarly, dipping anisotropic effects arise from the complexity of some of the subsurface features seen in thrust belt or subsalt environments. The validity of the model is checked by examining the depth-migrated gathers (pre-stack data) and the stacked response, where the gathers are expected to exhibit flat reflection events across all offsets, and the stacked response shows a reasonable match with the well data. It is sometimes difficult to determine a velocity model with accurate
anisotropic parameters, and if the velocity model used for depth migration is not optimum, the well ties are off, and so is the lateral positioning of the events.

To benefit from the advantages of depth migration, what has been done in the past is to convert the depth migrated data into time, perform the impedance inversion in time, and then bring it back to the depth domain. Thus the impedance inversion was being performed in the time domain. The suggested difference now is to bypass the conversion of depth data into time, and then after inversion the conversion of time data into depth again, and perform the impedance inversion in the depth domain itself. Due to the ease and accuracy of impedance data interpretation, and the fact that it allows an integrated approach to geological interpretation, impedance inversion plays an important role in reservoir characterization.

The first step in impedance inversion, whether in time or depth domain, is the well-to-seismic data correlation, as it relates the seismic data to stratigraphy and rock properties of the subsurface. The one entity that links the seismic trace at the location of the well and the reflection coefficient series constructed from the data is the seismic wavelet. As stated above, any processing involving wavelets has traditionally been done in the time domain. One main reason for this is that the shape of the wavelet remains consistent in the time domain (though the frequency of the wavelet decreases with time). In the depth domain, the shape of the wavelet changes as the velocity increases with depth due to compaction, or otherwise. When seismic data are converted to depth, the seismic wavelet undergoes a variable stretching that depends on the velocity. It gets stretched more in a high-velocity interval than a low-velocity interval. Also, because the velocity can vary spatially, depending on the geology, the seismic data in depth can have the wavelet stretch varying spatially as well. For carrying out impedance inversion on post-stack seismic data in the depth domain, a simple approach would be to follow the procedure for the seismic data in the time domain and let the stretch effects be in there, however small or big. Of course, by choosing a narrow depth window, the depth of the variable stretch in the vertical direction can be minimized.

There are a few ways that have been suggested to account for the variable spatial and temporal stretch. One of them is to replace the varying stretched wavelets in seismic depth data with an equivalent single-wavelet that is stretched in depth with a single velocity. Another reported approach overcomes the estimation of the wavelet and its convolution in the depth domain by using a pseudo-depth transformation. As the impedance inversion in depth evolves, the accuracy of such techniques will be established.

We understand thus that it is convenient to carry out the impedance inversion in depth directly, and we can take advantage of the superior imaging of the reflection detail, as well as overcome the pitfalls of the seismic data interpretation in time. The results that are being demonstrated for impedance inversion in depth by way of vendor presentations or in some publications that have started trickling in look promising. Besides the post-stack inversion, the pre-stack inversion results are also being discussed and look superior. Hopefully, we will witness interesting developments in carrying out impedance inversion in depth and the accurate interpretations that follow therefrom, in a quantitative way.