C. Wavelet estimation and calibration of well to seismic data: To extract the meaningful informations from impedance inversion and building the confidence in their correlation with rock properties, the calibration with rock properties at well locations using well logs, core data and borehole seismic information is very vital otherwise very purpose of these acoustic impedance volumes generated for reservoir characterisation will be lost.

Synthetic seismograms generated using sonic, density logs and checkshot or VSP surveys are used to calibrate geologic picks of wells in depth to seismic reflector two way time. The link between recorded seismic waveform, stratigraphy and rock properties is the seismic wavelet. Its accuracy is the fundamental for any well tie. Comparison of synthetic seismogram generated at well location with real seismic data offers physical insight into how well the seismic data have been processed and how well the forward modeled well logs depict actual in-situ geology. The major cause for misties between synthetics and real seismic data is that they do not contain the same wavelet. Synthetics are normally generated with a constant or minimum phase wavelet that is too simple to match with the complex seismic wavelet, which changes both vertically and laterally. A variety of methods are being used in practice for wavelet estimation. Some of them are:

1. Estimation of amplitude and phase spectra using deterministic measurements such as VSP analysis and marine source signatures (Johnston et al., 1997). But this method does not account for source radiation pattern and also do not include the effects of stacking and migration.

2. Estimation of amplitude and phase spectra using both seismic and well log measurements. Full wavelet and constant phase wavelet can be estimated by this semi-deterministic approach (Hampson and Galbrath, 1981). In this method estimation of wavelet critically depends on the quality of the tie between well logs and seismic.

3. Estimation of amplitude spectrum using seismic data alone. This is being done using statistical approach through autocorrelation or cross-spectral analysis or by maximum entropy spectral analysis (Lindsey, 1988, Brown et al., 1988). The phase is assumed known from other source in this method and it is assumed that seismic response is the result of convolution of minimum phase wavelet with a random series of reflectivity. This assumption often fails in reality.

The wavelet extracted from one of the above mentioned methods could be convolved with the reflectivity series to generate synthetics that matches well with the observed seismic data. The phase variation of extracted seismic wavelet and its tolerance limit is one of the most important aspects specially when striving for maximum accuracy in seismic-to well tie. Recently, White (1997) has emphasised the importance of well tie accuracy with reference to reservoir characterisation and stated that a phase error of less than 10 degree can be tolerated in case of acoustic impedance inversion. Beyond 10-degree phase error in wavelet may lead towards inaccurate impedance computation from seismic data. The estimated wavelet can be utilised to phase correct the seismic data to contain a constant zero phase wavelet. Further, using this extracted wavelet, full wavelet processing of seismic data can be carried out which may be helpful in reducing the phase variation and in broadening the spectral bandwidth. This in turn may enhance the high frequency signal component and hence the vertical and lateral resolution. This zero phase wavelet processed post stack seismic data can be utilised as an input for stratigraphic inversion.

D. Initial 3D geological model: In the stratigraphic inversion a priori reservoir model is needed. In order to obtain this model, petrophysical parameters from the well logs are interpolated between the wells in accordance with a structural framework. The structural framework is generated from seismic interpretation and geologic information of layers and their relationship with adjacent layers. For each well and geologic layer, concatenating velocity and density log generates a composite log. Principal component weights for composite logs are interpreted through out the model. By splitting the principal components of the composite logs into the velocity and density part, separate velocity and density volumes can also be generated from the same weights. Seismic to well tie is one of the most important step which provide time to depth conversion for obtaining best possible 3D geological model. These well logs also induce low frequency trend in acoustic impedance, which lacks in seismic data and is very crucial for making geologic interpretation. Calibrated stacking velocities can also be used in place of well logs for introducing low frequency trend in the initial geological model in the areas where well control is very sparse. It is important to note that low frequency phase misalignment tends to smear out sharp transitions and reduce the resolution of subtle stratigraphic features. The initial 3-D impedance model is a natural way to integrate various geoscientific data and provides a medium understood by geologists, geophysicists, petrophysicists and engineers.

E. Inversion techniques: Several different techniques are commonly used to perform acoustic impedance inversion. Some of them are summarised below:

1. Band limited inversion: This inversion is also known as recursive inversion. This is one of the most basic types of inversion and also the earliest methodology. It essentially assumes that seismic amplitudes are proportional to reflection coefficients and transforms input seismic traces...
to acoustic impedance traces. Inputs used for this inversion are usually wavelet processed which do not satisfy the basic assumptions, as spatial and temporal wavelet variations cannot be fully removed during processing. The results produced from this method usually have same bandwidth as available with seismic data. Therefore, this method does not offer a significant advantage relative to conventional interpretation.

**Sparse spike inversion**: Sparse spike inversion estimates the reflectivity series that would approximate the seismic data with a minimum number of spikes. Nonuniqueness is taken care of by applying the sparse reflectivity criterion. For this purpose, maximum likelihood deconvolution and L1 norm algorithms are being commonly used. Sparse spike inversion tends to remove the embedded wavelet from the data, the inversion results are less dependent on initial guess model, broadband for the higher frequencies, maximising vertical resolution and minimising the tuning effects.

**Model based inversion**: This inversion is also known as blocky inversion. Model based inversion models the subsurface as layers or blocks in terms of acoustic impedance and time. The starting model is defined by a few 3-D main time horizons. Well logs tie main time horizons to seismic data and define the impedance bounds for each model layer. Impedance within each layer may vary laterally and vertically. Impedance bounds are set to keep the optimised model laterally smooth and within given limits. The nonuniqueness is taken care of by restricting number of layers relative to the number of seismic samples. Using iterative forward modeling schemes, the starting impedance model is being perturbed until it’s forward model matches with real seismic traces. This method has the advantage of allowing some degree of control over the starting point and hence the resulting inversion but final output of inversion is highly dependent on initial guess model and very sensitive to the estimated wavelet.

**Geostatistical inversion**: Geostatistical inversion combines geostatistical data analysis and modeling with seismic inversion. Geostatistical inversion of acoustic impedance does not need to numerically simulate the low frequency informations. The low frequency component is naturally blended into the geostatistical inversion. Geostatistical analysis generates spatial statistics, vertical variograms are generated from well log measurements and horizontal variograms are estimated from the acoustic impedance values afforded by starting impedance model generated from seismic data. Starting from the wall control points, geostatistical modeling simulates data at grid points. While carrying out the inversion, the simulated points are modified so as to agree with both well and seismic data.

All the model based inversion methods belong to a category called local optimisation methods. A common characteristics is that they iteratively adjust the subsurface model in such a way that the misfit function decreases monotonically. In case of having good well control, which provide good starting model, the local optimisation methods produce good results. For sparse well control or where the correlation between seismic events and nearby well control is made difficult by fault zones, thinning of beds, local disappearance of impedance contrast, or the presence of noise, these methods do not work satisfactorily. Under such circumstances, global optimisation techniques such as simulated annealing, genetic algorithms, neural network and taboo search etc. are needed. Global optimisation methods employ statistical techniques and give reasonably accurate results of inversion.

**Neural network inversion**: A neural network is a mathematical algorithm, which encodes a relationship between two data sets. That relationship may be nonlinear, and it is not necessary to know what relationship is used in the neural network. Neural networks, due to their properties such as powerful pattern matching capability, adaptive ability, tolerance, robustness etc., have been involved in numerous applications in the various areas of geophysical prospecting including the time varying signal processing and stratigraphic interpretation. The most commonly used neural network schemes in inversion are (1) Multi-Layer Feed Forward Neural network (MLFN) and (2) Probabilistic Neural Network (PNN). Using neural network consists of three steps. First step is training of network in which a relation is established between two data sets and learned by neural network. This is being done iteratively for the search of optimum weights using global optimisation technique to each attribute for training the network. Second step is the validation of trained neural network at known well locations if they were not used during training. This process provides the confidence level about the accuracy of neural network inversion. The third step is the application of trained and validated neural network on a larger volume for acoustic impedance inversion. Analysis window for training and application of neural network is very crucial because of two reasons (1) Training and application of neural network can be very time consuming and computer intensive if applied to the entire window. Both these functions depend on the number of samples in the...
training window, and (2) the expected relationship may be time variant and expected to be less valid outside the training windows. These reasons suggest the application of neural network over a small window around the target zone for achieving higher accuracy. The neural network inversion provides much higher accuracy and resolution as compared to earlier described model based inversion methods.

F. Validation of inversion results: Since, all the post stack inversion algorithms suffer from the nonuniqueness problem, it is necessary to validate the inversion results from the actual measured impedance at different well locations. Final inversion volume consists of micro-layers with time and impedance values, which can be compared with all available wells to qualitatively and quantitatively examine the inversion results. This estimation of error through validation at well locations provides an idea about the robustness of a particular inversion scheme on others and its suitability. If estimated errors are beyond acceptable limit, it allows relooking the inversion process, checking various inputs and constraints used during inversion for the improvement of the inversion results. Once inversion results are found satisfactory at known well points, impedance volume can be used to learn how the changes in acoustic properties affect the seismic response and thereby control the reservoir properties because it acts as a link between seismic attributes and reservoir properties.

Examples showing advantages of stratigraphic inversion:

The several advantages of acoustic impedance over conventional seismic data mentioned earlier in this paper have been demonstrated through some of the examples. These examples have utilised the complete inversion scheme discussed in the previous section:

Example-1:

To demonstrate the importance of seismic inversion, a wedge model and its seismic as well as inverted output representation is shown in Figure(4). The geological model represents a simple high impedance wedge embedded in a low impedance background (Figure 4a). The zero phase seismic response of the geological model generated using 35 Hz Ricker wavelet in standard wiggle trace and colour density with wiggle over lay have been displayed in Figures (4b and 4c). The tuning effect can be easily observed in synthetic seismic section as the wedge thins and side lobe interference occurs within wedge itself. From the seismic data shown in Figure(4b and 4c), it is possible to interpret the general structural trend but side lobes give the impression of pseudo reflections inside the wedge. This makes it difficult to know whether there are any internal structure or lateral variations in the properties of the wedge. Figure(4d) shows the result of acoustic impedance inversion obtained by inverting the synthetic seismic data. Tuning effect is diminished and internal geometry is eliminated. The resulting inverted wedge is a more accurate spatial representation of the original model and provides absolute AI values that match with the original model.

Example-2:

Another compelling example of inverting seismic data is illustrated in Figure(5). This example demonstrates the importance of inversion where impedances are having varying degree of gradational changes. Such changes are impossible to detect in conventional seismic data, which shows homogeneous and uniform medium in these zones. A geological model having varying degree of changes in impedance are shown in Figure (5a). The computation of density for layers having gradational velocity variation has been executed using Gardner’s empirical relation. Synthetic seismogram was generated using 35 Hz zero phase Ricker wavelet. The generated synthetic seismogram is shown as wiggles along with amplitude in colour background in Figure(5b). Comparison of geological model with synthetic shows that there are four interfaces: 50 ms, 150 ms, 350 ms and 520 ms. It is important to note that each interface represent same changes but in varying gradational degrees. The seismic data identifies the sharp changes at 50 ms and 520 ms. the top of second interface can be identified at 150 ms but it is not apparent that the interface is a gradational coarsening upward sequence because the seismic do not recognise the base of the event. The synthetic seismic fails to recognise the most gradual interface at 350 ms. On the other hand inverted section shown in Figure (5c) has effectively demonstrated all these variations of rock properties.

Example-3:

It is well known that well logs are able to resolve vertical interval of less than one feet but they can provide information only 6 to 8 inch away from the borehole. On the other hand, seismic data are not capable of providing higher vertical resolution comparable to well logs but their horizontal resolution is as large as the seismic survey. This leads to the basic difference in the dimension of resolution between logs and seismic data. Thus, well logs have excellent vertical resolution and poor horizontal resolution, where as seismic data have excellent horizontal resolution and poor vertical resolution. Post stack stratigraphic inversion integrates borehole, geological and seismic data and provide acoustic impedance of higher resolution. Thus, acoustic impedance maximises vertical resolution, bridges the gap between vertical resolutions of seismic data and well log measurements, simplifies the lithologic and stratigraphic definitions of the subsurface. This can be clearly seen in the example shown in Figure (6), which displays seismic, acoustic impedance and well log data along with lithology. Acoustic impedance section clearly shows the delineation of thin layers. For each layer the impedance is constant vertically, but vary laterally. This layer wise display is very useful for visualising the individual layer with improved vertical resolution. This enhanced vertical resolution is the result of the parameterisation of the initial impedance model which is micro layered with respect to the frequency content of the seismic data. In a good quality high-resolution seismic data, it is even possible to obtain the maximum resolution of the order of the sampling rate of the
Fig. 4a: Schematic diagram of wedge shaped geological model.

Fig. 4b: Synthetic seismogram generated from wedge model using 35 Hz Ricker wavelet in wiggle.

Fig. 4c: Synthetic seismogram displayed in wiggle with coloured amplitude background.

Fig. 4d: Inverted section of synthetic seismic section.
Fig. 5a: Geological model having gradational changes in acoustic impedance.

Fig. 5b: Synthetic trace display in wiggle with coloured amplitude in background.

Fig. 5c: Inversion result showing gradational variation of impedance.