Velocity determination for pore-pressure prediction

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Overpressured formations exhibit several of the following properties when compared with a normally pressured section at the same depth (Dutta, 2002): (1) higher porosities, (2) lower bulk densities, (3) lower effective stresses, (4) higher temperatures, (5) lower interval velocities, and (6) higher Poisson's ratios.

Borehole data measure several of these properties and can be used to determine overpressures. Also, seismic interval velocities get influenced by changes in each of the above properties, and this is exhibited in terms of reflection amplitudes in seismic surveys. Consequently, velocity determination is the key to pore-pressure prediction.

Overpressure detection from borehole data. Changes in pore pressure can be recognized on regular formation evaluation tools such as sonic, resistivity, porosity, and density logs. These logs show the effects of pore pressure because of the relationship between compaction, porosity, density, and the electrical and acoustic properties of sediments. As a rock compacts, the porosity is reduced and the density increases, which also causes the bulk modulus and shear modulus to also increase because of increase in grain contact area and grain contact stress. This process continues until the mechanical process of compaction is slowed by either the stiffness of the rock frame or by increases in pore pressure that resist further compaction. In cases where the sealing rocks allow fluid pressures to counteract the vertical stress and undercompaction occurs, the result of this process is to slow down the decrease of porosity and increase in velocity and density, but *not* to stop it totally. As such, undercompacted intervals will still follow the normal compaction pathway but the rocks in such a condition will show higher porosities and lower velocities than a normally compacted rock at the same depth of burial. This effect can be seen on log displays (Figure 1).

When unloading pressure mechanisms occur in the subsurface, the increase in fluid pressure causes the compaction process to stop, which causes the porosity and density to cease changing with depth of burial. As the fluid pressure increases and the effective stress drops, the rock is not able to increase its porosity because the compaction process is irreversible. Therefore, the grain contact area also is essentially unchanged. However, the increase in the pore pressure does cause a reduction in the grain contact stress, which causes the velocity to drop as the grain stress is lowered by the increase in pore pressure. This produces the classic signature of unloading as shown in Figure 1 in the deeper section where the density log ceases changing and the sonic log undergoes a sharp reversal. This effect can be recognized very easily by crossplotting sonic and density logs for a well (Figure 2). In such plots, the unloaded zone becomes very obvious because of the abrupt change in the velocity density plot as the velocity drops and the density stays the same.

Zero-offset vertical seismic profiles can be used for detection of high pressure zones in the subsurface ahead of the drill bit using seismic inversion methods. Figure 3 shows a pseudo interval velocity trace in well A-1 from eastern India. The inversion was done using the procedure outlined by Lindseth (1979). A well about 1.5 km from A-1 had encoun-

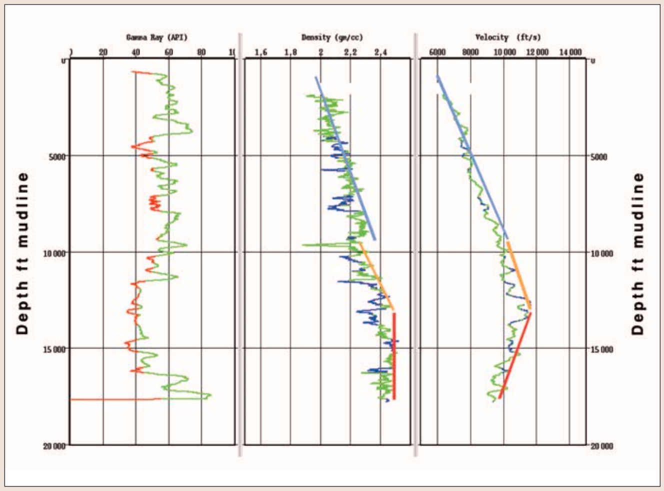

Figure 1. Velocity and density logs showing the physical properties of normally compacting rocks (blue trend lines), undercompacted rocks (orange trend lines), and unloading (red trend lines).

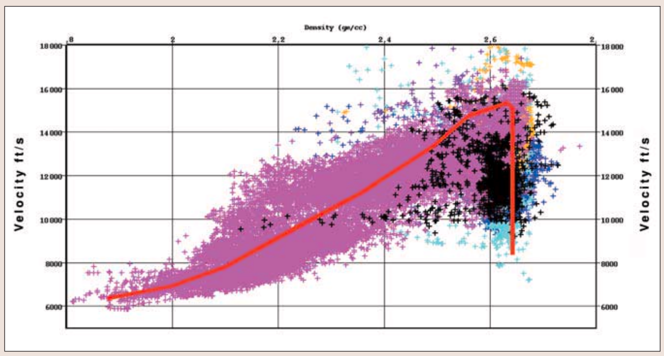

Figure 2. Example of the velocity-density crossplot method for recognizing unloading. The abrupt decrease in velocity at a constant density is the signature that is diagnostic of this process.

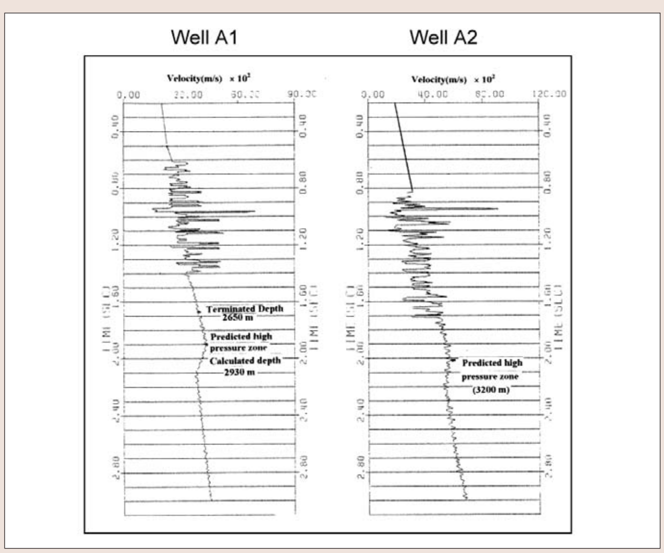

Figure 3. Predicting high-pressure zones ahead of the drill bit (images courtesy of ONGC).

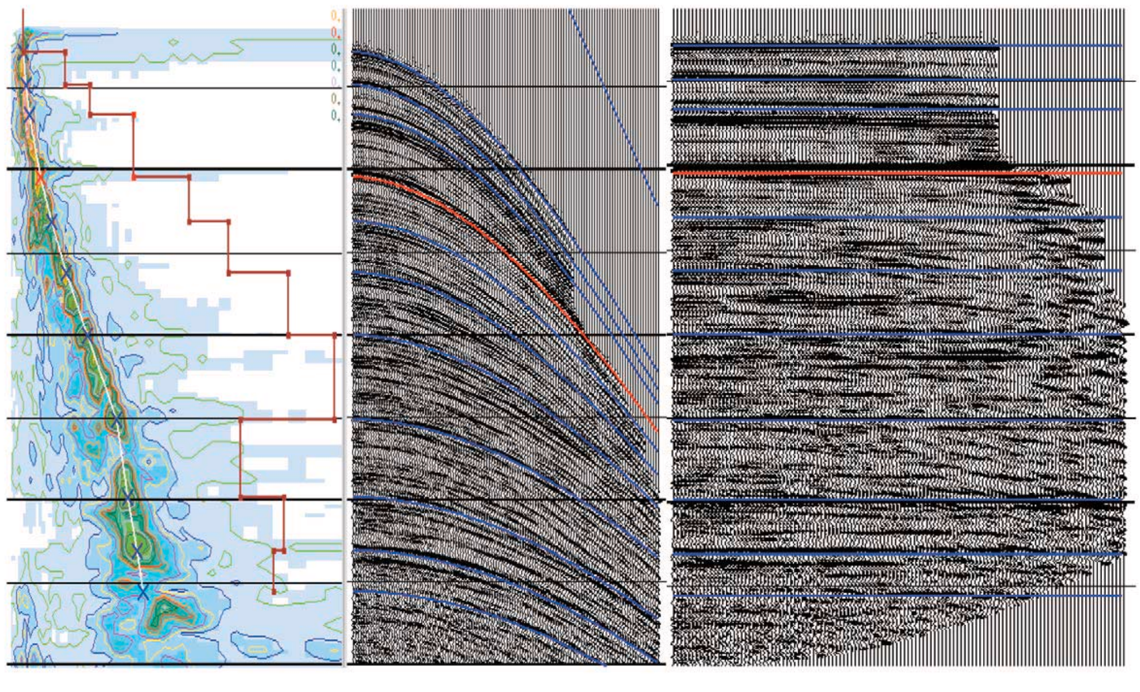

Figure 4. Traditional semblance-based velocity analysis display showing a semblance panel (left), uncorrected gather (middle) and NMO-corrected gather (right) (after Bell, 2002).

tered a blowout at 2100 m. Being adjacent, high pressure was expected in this well also at around the same depth. VSP data were acquired in this well and the pseudo interval velocity trace generated from the corridor stack trace. As is evident from the "knee" (Figure 3), high pressure was predicted at 2930 m. However, due to some practical difficulties, drilling for this well was suspended at 2650 m, and no high pressure zones were encountered up to that depth.

Another well A-2, about 2 km from A-1, was drilled (depth not available) and VSP data were acquired and processed. The "knee" seen on the pseudo interval velocity trace indicated that high pressure was to be expected at 3200 m. Drilling was continued further, and high pressure was encountered at 3180 m in accordance with the prediction. At the time this work was done, pressure indications were read off from the interval velocity traces.

Overpressure detection from seismic data. The estimation of pore pressures from seismic data uses seismically derived velocities to infer the subsurface formation pore pressure. The Eaton method uses a direct transform from velocity to pore pressure, while the Bowers method estimates the effective stress from the velocities and then calculates the pore pressure. There are many different types of seismic velocities, but only those velocities that are dense and accurate and are close to the formation velocity under consideration, will be of interest. The following methods have been used with varying degrees of success.

Dense velocity analysis. Velocity information is determined from seismic measurements of the variation of reflection time with offset (i.e., CDP gathers). It is the hyperbolic characteristic of these reflection time-offset curves which forms the basis for computation of velocity analysis. A statistical measure of trace-to-trace similarity (cross-correlation or semblance) is employed to determine resulting amplitudes which are posted on a spectral display.

Figure 4 shows traditional velocity analysis carried out with semblance analysis using hyperbolic search on a CDP gather. Individual velocity picks are marked on the display keeping in mind the energy maxima and connecting all primary energy peaks yields the rms velocity function (white line) and its calculated interval velocity (red line) derived using the Dix equation. Computing interval velocities from stacking velocities can often be inadequate as Dix's equation assumes flat layers of uniform velocity. For geopressure prediction, the goal is to pick velocities to optimally flatten the data (Figure 5). It is often observed that basic processes such as how the data are muted can improve or degrade the semblance picking process (Figure 6). The biggest difference in velocity analysis for geopressure prediction is that surface-like faults, which are usually ignored in traditional velocity analysis due to the absence of semblance events at the fault surface, are actually picked to assure that velocity changes across the fault are honored. It is also often observed that the quality of velocity analysis is directly affected by the quality of the underlying imaging. Figure 7 shows three CDPs on a seismic line with variable data quality. This example shows how significant the image quality is for good velocity analysis.

Geologically consistent velocity analysis. Traditional stacking velocities, while producing good quality stacks, usually do not follow key geologic features like faults, lithologic boundaries, and major sequence events in a consistent fashion. In the traditional approach, the 3D velocity field is generated by interpolating within the picked velocity functions. This can lead to "bull's eyes" in the interval velocity maps generated for QC. Also, for thin layers, a small variation in the rms velocity picking causes a large change in the interval velocity. These problems are addressed by smoothing the velocity field significantly. Severe smoothing often smooths out some of the subtle and real velocity variations along with the noise. Geologically consistent velocity analysis addresses these shortcomings and can also use well logs to choose key surfaces for picking velocities. Seismic time horizons are first interpreted on a preliminary stacked volume. The well control in the area is combined with these horizons to produce an initial interval-velocity field. This regional velocity field is superimposed on the displays. The processor now picks the velocities at several locations along the line, changing the model wherever necessary. The veloc-

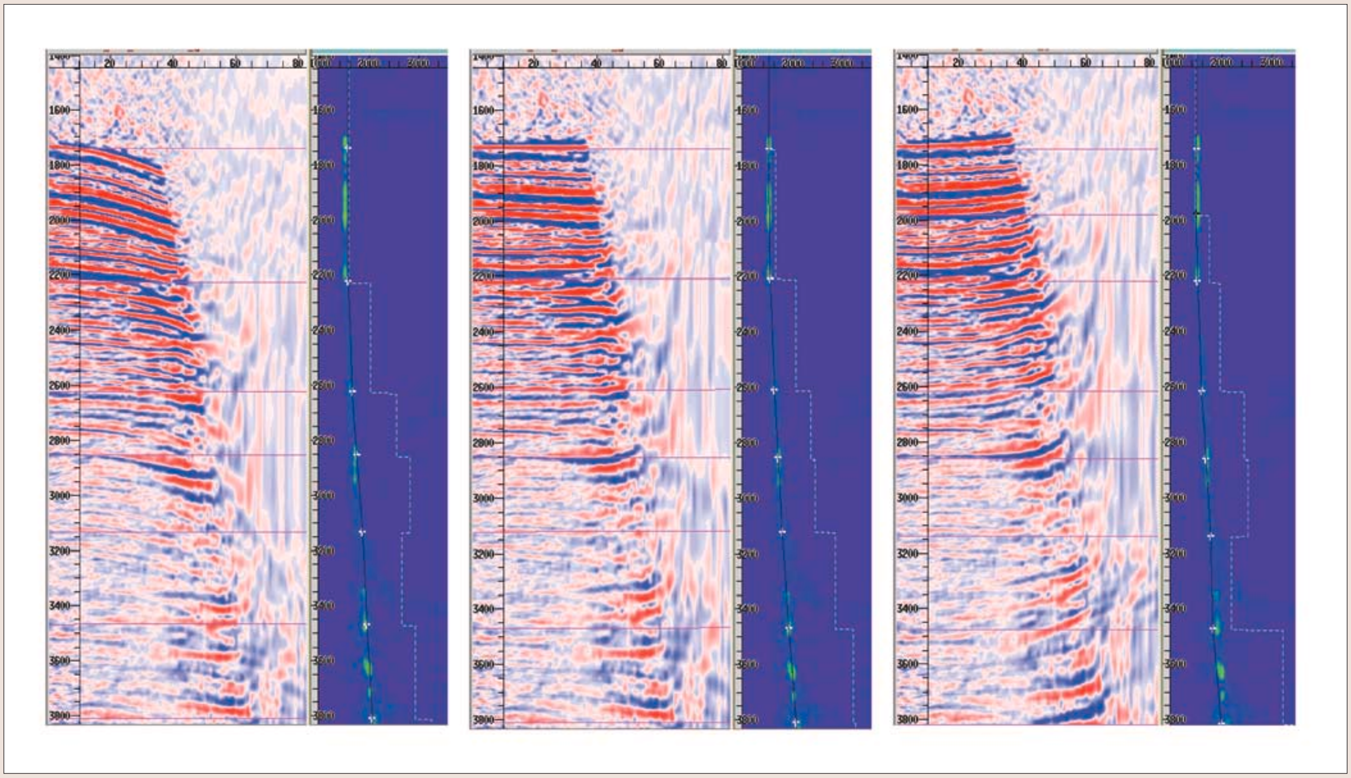

Figure 5. Traditional semblance-based velocity analysis display comparing an undercorrected gather (left) and an overcorrected gather (right) to the properly flattened gather (middle) (after Bell, 2002).

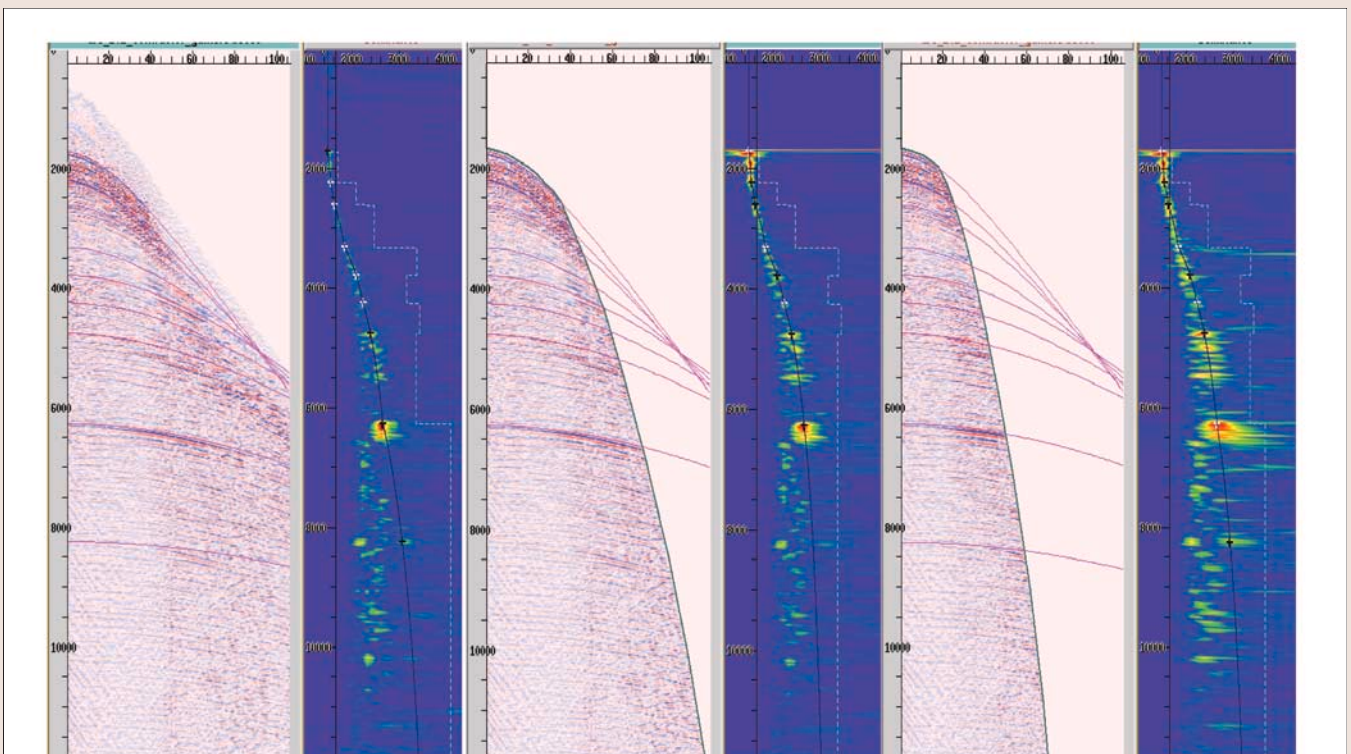

Figure 6. Traditional semblance-based velocity panels showing the effect of different mutes. The left panel has no mute which degrades the shallow semblances while the right panel has a harsh mute that smears the semblances (after Bell, 2002).

ities are picked as interval velocities and converted into stacking velocities. Such a velocity model, when properly designed, will honor both the seismic data and the well control.

Figure 8 compares traditional and geologically consistent velocities. The sonic well log in time (blue) is overlain on the velocity curves (red). Note that while the traditional velocities yield a "smoothed" approximation to the well log, the geologic velocities follow the detail of the geologic layers (i.e., the changes in the velocity on the sonic log are

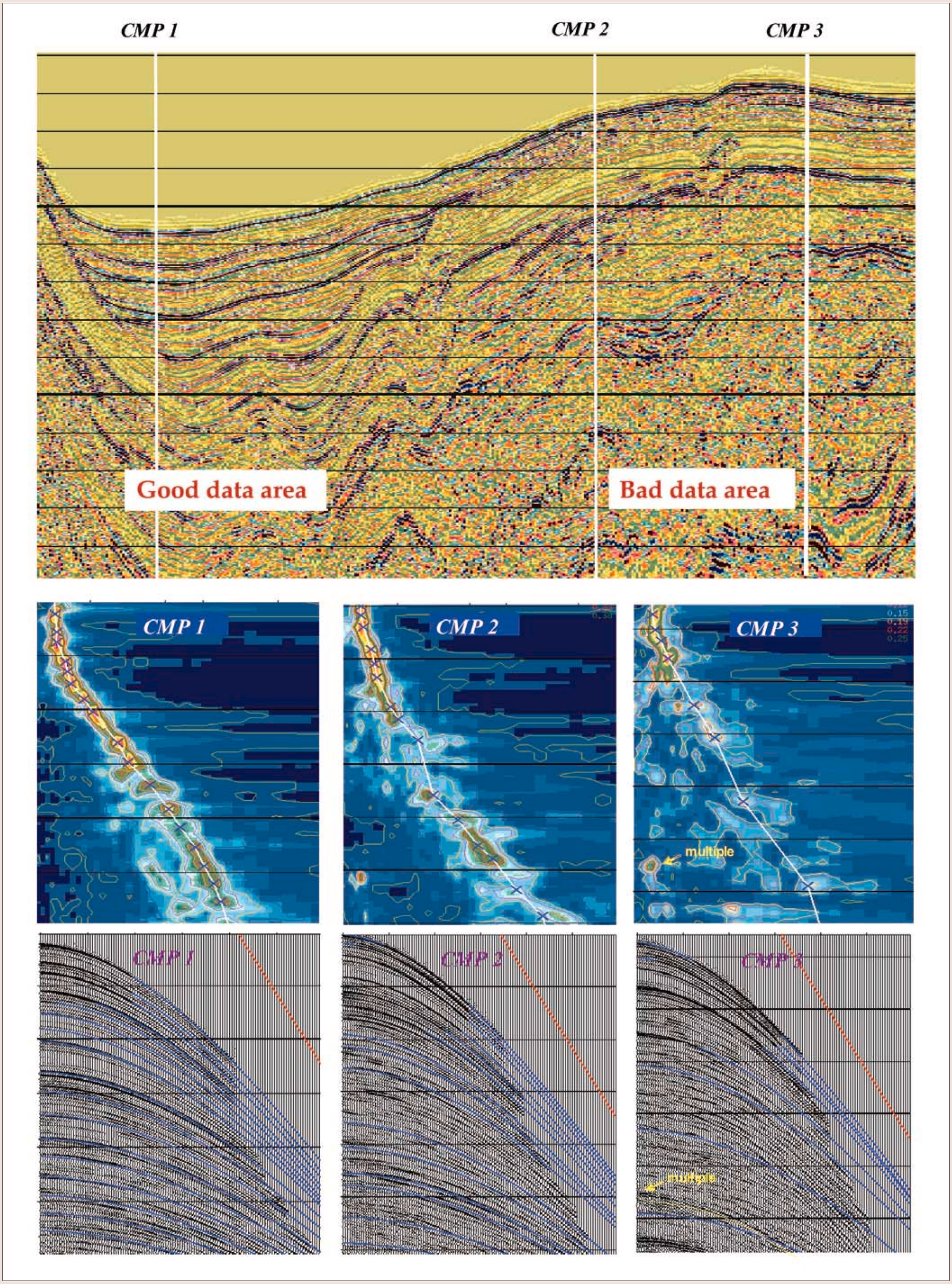

Figure 7. *Seismic section (upper panel) showing location of three CDP gathers and their relationship to image quality. The image quality influences the semblance strength from CDP 1 (excellent quality) to CDP 3 (poor quality) (after Bell, 2002).*

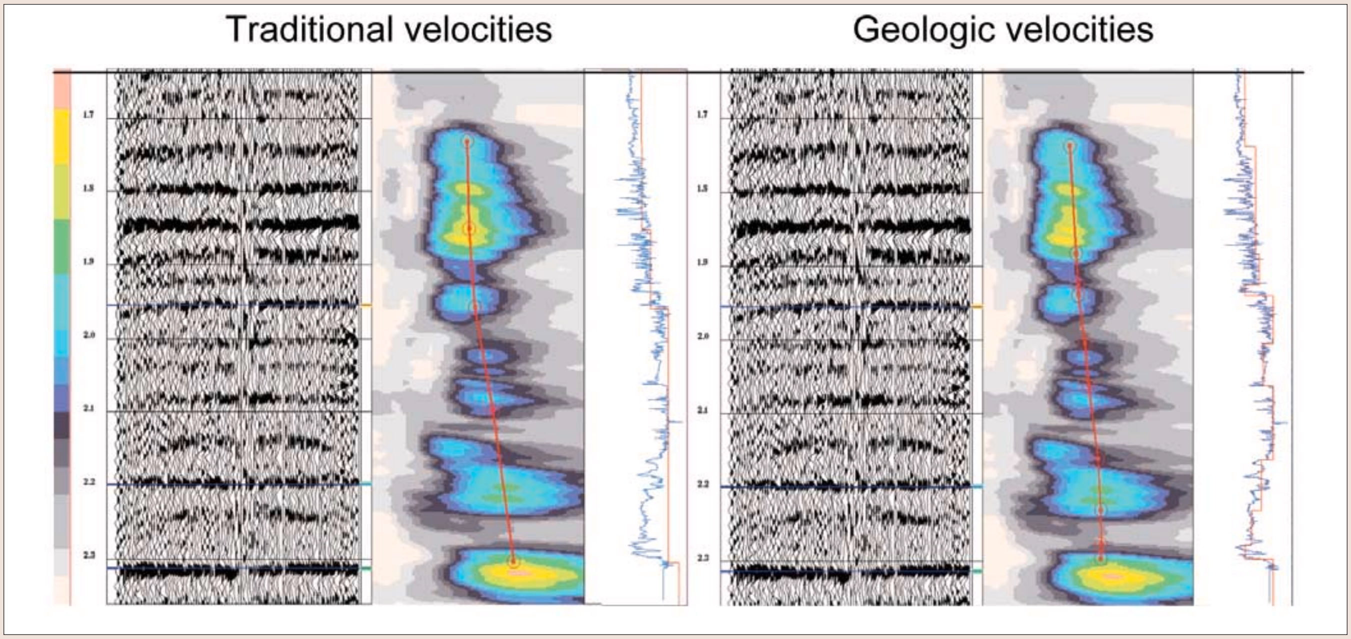

Figure 8. A comparison of an enlarged view of a portion of the velocity display with and without well log calibration. While the two techniques produce good NMO corrections, they use very different picking strategies (after Crabtree et al., 2000).

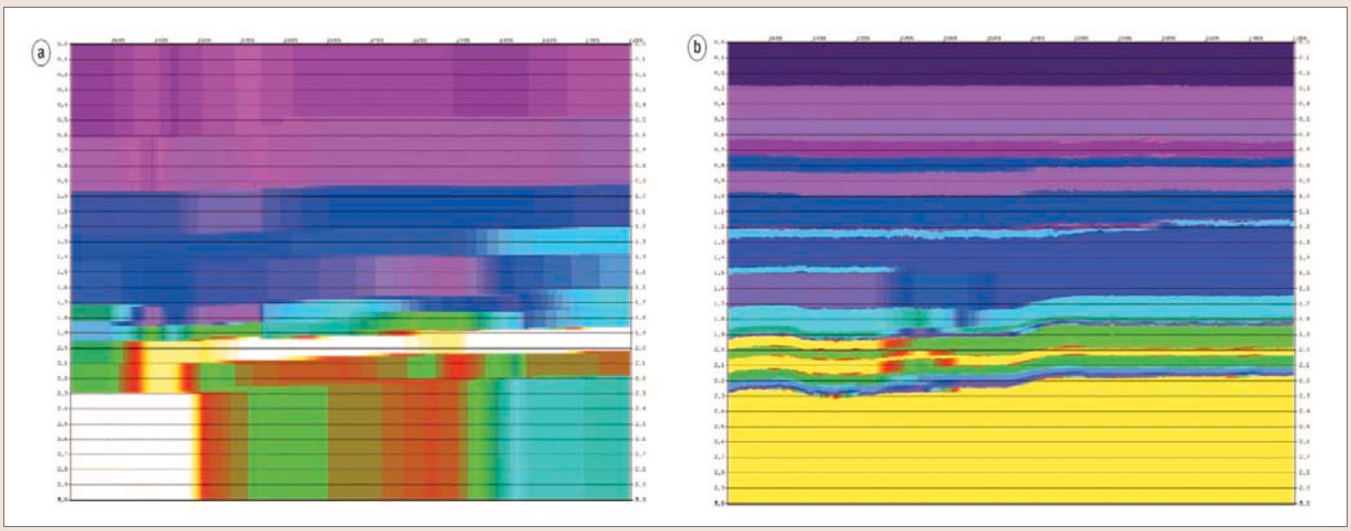

Figure 9. Traditional velocities (left) and geologic velocities (right) produced this interval velocity field (after Crabtree et al., 2000).

followed much more closely).

Figure 9 illustrates how the use of geologically consistent velocities has improved the accuracy and provided greater spatial consistency in comparison to the more traditional way of picking velocities.

Thus the geologic approach to velocities ensures that the geologically consistent velocities are horizon consistent, and ensure that bull's eyes are avoided and realistic values that tie to the wells at each line intersection are consistent. While these velocities are geologically more meaningful and correct, they need to be used carefully. Another point is that such a velocity field may not properly flatten the gathers. If this is an issue in the area of interest, then an alternative method would need to be explored. The geologically consistent approach to velocity analysis is sometimes augmented with spatial modeling (geostatistics).

Horizon-keyed velocity analysis (HVA). Traditional velocity analysis provides the velocity functions along the seismic profiles at selected points. Even for cases where the S/N ratio is above moderate and the structure is not complex, the accuracy is not sufficient for computation of reliable interval velocities, depth sections, and for getting good quality migrations.

Horizon velocity analysis provides velocities at every CDP location along the profile (Yilmaz, 2001). The velocity analysis is computed for a small number of time gates centered on normal-incidence traveltimes that track given reflection horizons. Because only a few time gates are to be considered and the range of trial velocities is limited, the computer time is used in a better way in conducting an intensive analysis on important events, than on time zones between horizons.

Figure 10 shows a reflecting horizon and its associated computed HVA. Once HVA computation is completed for the main horizons in the section, it is possible to build up a grid by computing the interval velocity between these main horizons.

Horizon velocity analysis can provide high spatial resolution, but the temporal resolution may be low for pore-pressure prediction applications. Due to this reason, this

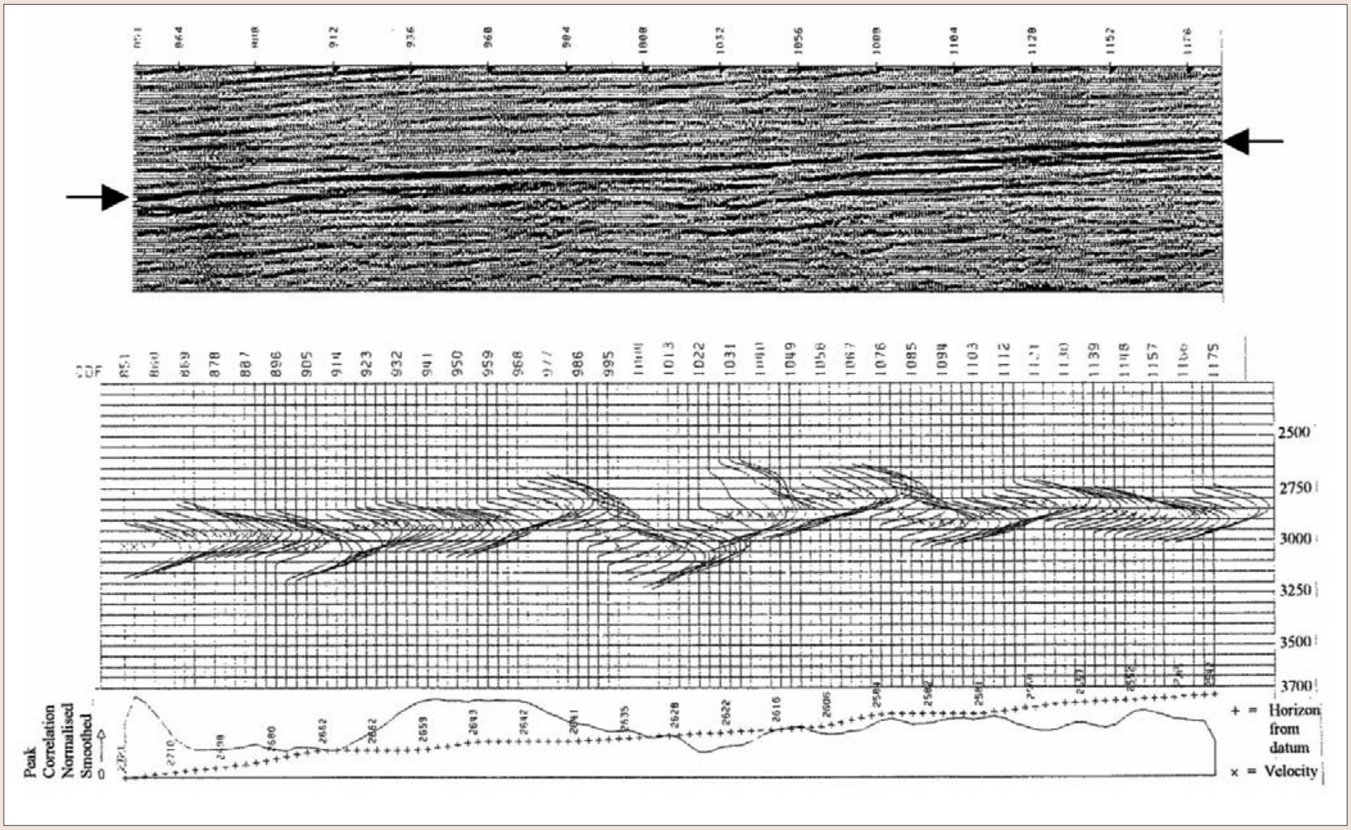

Figure 10. Horizon velocity analysis carried out for the horizon indicated on the seismic segment with arrows. Notice the variation in the rms velocity along the horizon (images courtesy of ONGC).

approach should be applied in conjunction with another technique where this information proves useful.

Automated velocity inversion. An automated velocity inversion technique, proposed by Mao et al. (2000), assumes stacking velocities are equivalent to rms velocities, an assumption that would require appropriate corrections for reflector dip, nonhyperbolic moveout, and event timing. Such assumptions can only be satisfied with prestack depth migration as demonstrated by Deregowski (1990). The data input to this method are migrated image gathers. The method comprises a series of algorithmic components:

1) As the first step, reflection events in 3D space are analyzed. Those events and their corresponding stacking velocities that exhibit maximum spatial consistency are picked.
2) Next, treating the stacking velocities as rms velocities and using a least-squares optimization procedure, constrained interval velocities are computed.
3) These velocities are then smoothed using a cascaded median filter, keeping in mind the desired resolution limits in terms of the magnitude and the lateral extent of the smallest velocity anomaly to be resolved.

The method yields a 3D velocity model in which steep dips and relatively rapid velocity variations have been handled. Application of this velocity procedure to pore-pressure prediction in a deepwater basin, offshore West Africa, has been demonstrated by Banik et al. (2003).

Reflection tomography. Reflection tomography is an accurate method for velocity estimation as it replaces the layered medium, hyperbolic moveout, and low-resolution assumptions of conventional velocity analysis with a general ray-trace-modeling-based approach (Bishop et al., 1985; Stork, 1992; Wang et al., 1995). While conventional velocity analysis evaluates moveout on CMP gathers, tomography uses prestack depth-migrated common image point (CIP) gathers for the same process. This latter analysis is based on the premise that, for the correct velocity, PSDM maps a given reflection event to a single depth for all offsets that illuminate it (Woodward et al., 1998; Sayers et al., 2002). Tomography takes into account the actual propagation of waves in the media and is able to update velocity values in the model along the raypath. Tomography also provides a dense horizontal and vertical sampling. Both these characteristics make the technique very appropriate for building accurate velocity models for geologically complex areas and where velocity varies rapidly. Two different types of tomographic solutions are usually followed—volumetric or layered and grid or nonlayered (Sugrue et al., 2004).

The layered tomographic approach characterizes the model space with volumetric elements or layers following geologic boundaries or interpreted reflection horizons, with each element assigned a constant velocity value or a velocity gradient. Ray tracing performed on the initial model creates modeled traveltimes, which are compared to the reflection horizon traveltimes. A least-squares optimization minimizes the difference between these two traveltimes by adjusting the depth and/or the velocities. This is done iteratively till the solution converges.

The grid or layered approach divides the model space into a framework of regular cells or grids each having a constant value. Residual moveout picks on depth image gathers are generated on a grid. The velocity model values are then adjusted iteratively to minimize the residual moveouts on the image gathers and in the depth migration process till the solution converges.

The choice of one or the other is largely dependent on

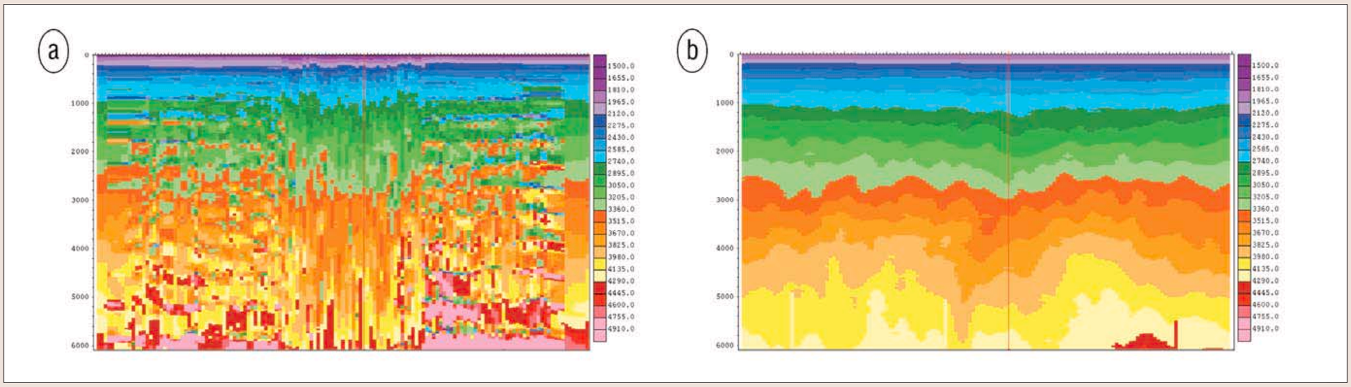

Figure 11. Raw dense velocity picks (a) and the resulting smoothed velocity field used for migration (b) (after Huffman et al., 2003).

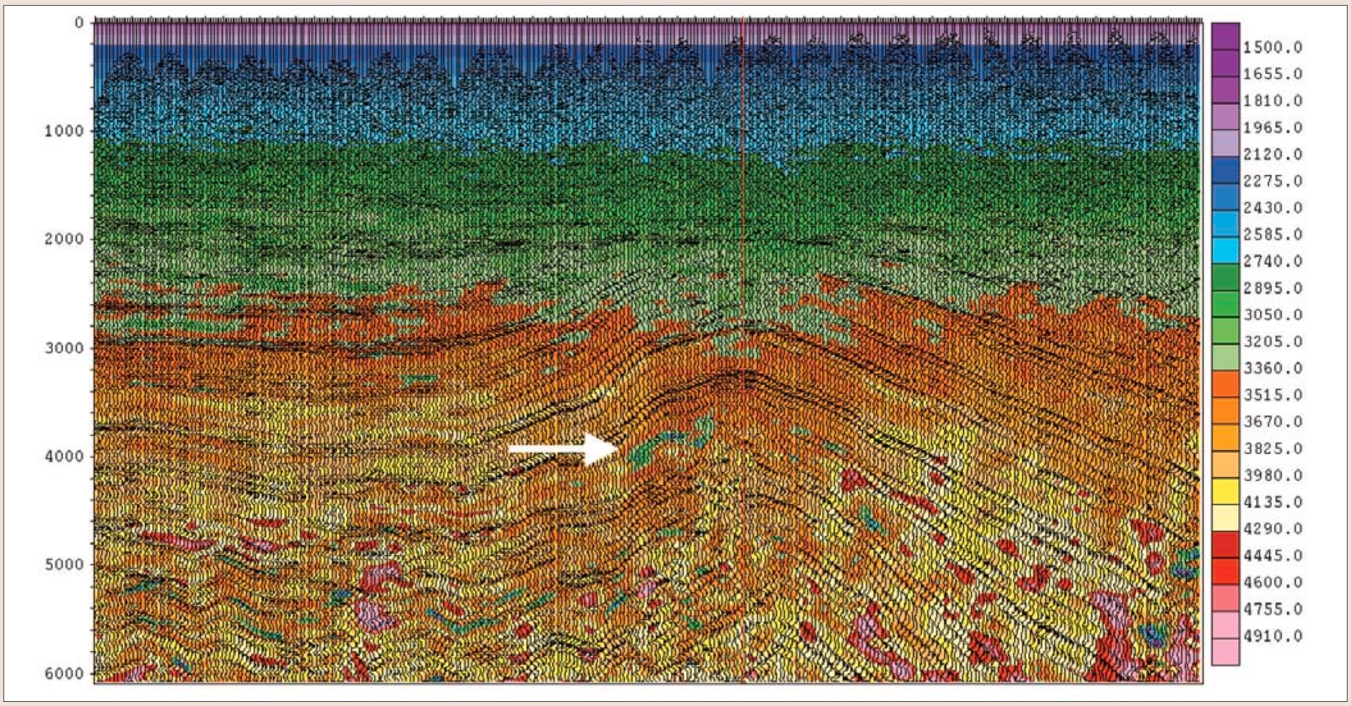

Figure 12. Velocity section with stack trace overlay from Figure 11 after application of residual velocity analysis. Note the low-velocity gas sand that shows no stacked amplitude (after Huffman et al., 2003).

the geology of the area being considered. Layer-based tomography is usually applied in areas where the stratigraphic sequences can be identified clearly and horizon picking is easy. For those areas where this is not possible, the grid-based approach is preferred.

Sayers et al. (2002) demonstrate the difference in pore-pressure prediction by using the two approaches explained above. The tomographically refined velocity model yields a pore pressure spatial distribution that is easy to understand and comprehend.

Zhou et al. (2004) have described a tomographic velocity analysis method in which interval velocities and anisotropy parameters are first estimated and then incorporated into the ray tracing to flatten events in the common image gathers. For anisotropic media, this process helps image subsurface structures accurately.

For areas that have lateral velocity variations and are structurally complex, tomographic inversion gives more accurate velocity models and also justifies the extra effort and cost.

Residual velocity analysis. One of the serious problems in doing AVO analysis is obtaining precise stacking velocity measurements for its proper application. Velocity errors that have little-to-no effect on conventional stacking can cause significant AVO variation several times larger than those predicted by theory. Shuey's formulation for AVO yields an intercept and a gradient stack. While the intercept represents the zero-offset reflection coefficients, the gradient is a measure of the offset dependent reflectivity. Swan (2001) studied the effect of residual velocity on the gradient and developed a methodology to minimize the errors by utilizing a new AVO product indicator which he called the *residual velocity indicator* (RVI). This indicator equals the product of an AVO zero-offset stack and the phase quadrature of the gradient. The sign of the correlation indicates whether the NMO velocity is too high or too low. The optimal NMO velocity minimizes this RVI correlation. Residual velocity analysis produces a null point at every sample point, which facilitates the generation of a velocity value at every data sample. Thus, a high-resolution velocity field is generated. So, while traditional stacking velocities are generally picked with semblances, optimum velocities for AVO are picked using RVI, which is more sensitive to velocity variations than a standard semblance estimate. The residual velocity method, which was popularized by ARCO with the AVEL algorithm, also allows accurate prediction of velocities in

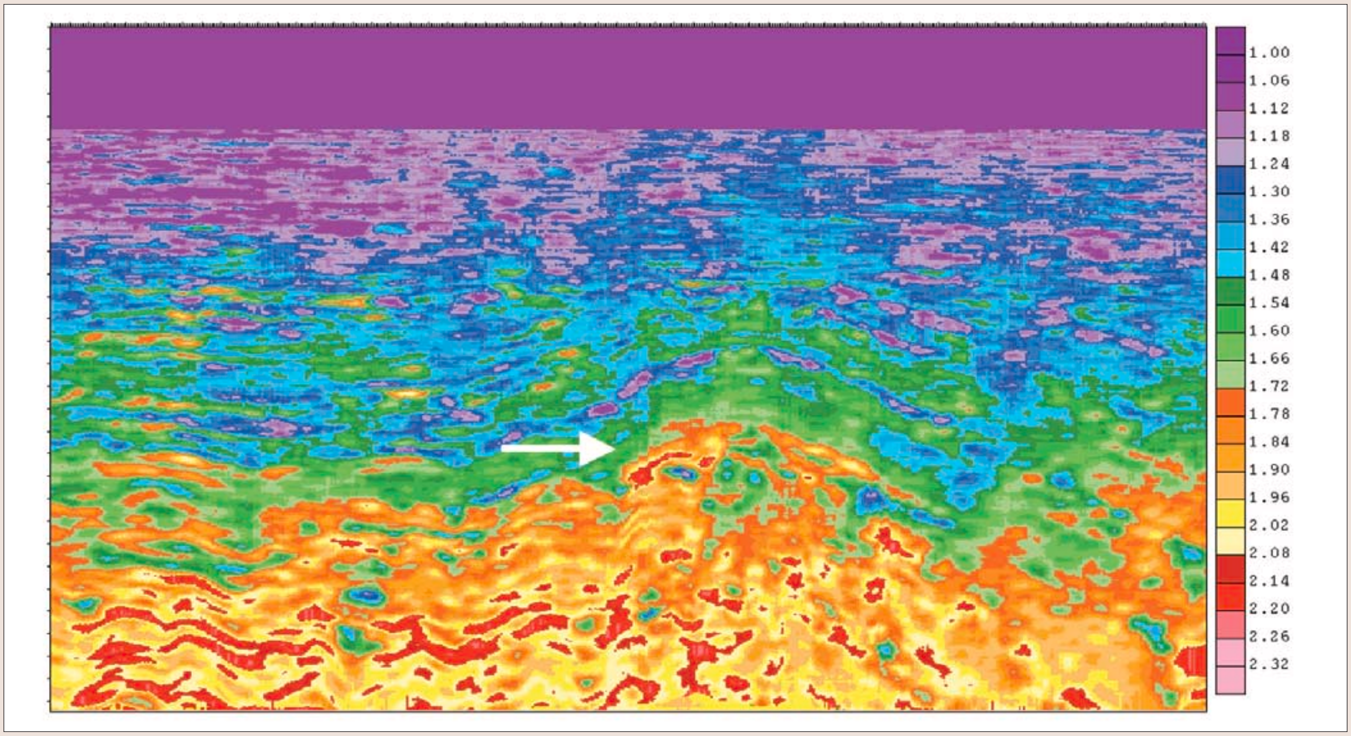

Figure 13. *Pore-pressure section for the velocities in Figure 12 showing the details generated by the residual velocity method. The gas reservoir is marked by the white arrow (after Huffman et al., 2003).*

the presence of type II polarity-reversing AVO events which cause problems for traditional semblance analysis. Spatial and temporal averaging forms part of the process to obtain a smooth and a continuous residual velocity estimate.

Figure 11 shows traditional dense velocity analysis (Figure 11a) and the smoothed equivalent velocity field used for migration (Figure 11b). This section shows virtually no details of the underlying velocity field. Figure 12 shows the same section after application of residual velocity analysis. Note the details in the velocity field that follow the reflectors, including a type II AVO gas reservoir (white arrow) that displays a low velocity in a section with little stacked amplitude. This aspect of the residual velocity technique makes it particularly valuable as a data conditioning tool for geopressure, AVO, and inversion studies.

Figure 13 shows the result of transforming the velocities in Figure 12 into pore pressure gradient in equivalent density units. The resulting section demonstrates the level of detail that can be derived in pressure prediction using residual velocities. The figure also demonstrates a pitfall of pressure prediction where hydrocarbons are present. The gas reservoir identified in the velocity display in Figure 12 shows an anomalously high pore pressure in Figure 13 which is actually caused by the gas effect in the pay zone and is not a pressure-related effect. It is important to note that hydrocarbon effects and nonclastic rocks such as carbonates and volcanic rocks violate the calibration assumptions for pressure prediction, and thus will give erroneous pressure values. The residual velocities can in some cases allow the user to isolate these zones so that they don't negatively impact the overall prediction process.

The computation of residual velocities uses a number of assumptions, an important one being that the velocity is assumed as constant and that AVO behavior is consistent in the RVI window. Short offset for moveout and AVO analysis is another assumption. Ratcliff and Roberts (2003) showed that these and other assumptions are often invalid in real data and this adds noise and instability to the iteration process. By monitoring the convergence criteria, it is possible to reduce or avoid these instabilities. Ratcliff and Roberts extended Swan's method in that once RVI estimates are computed, they are used to update the velocity field and any subsequent moveout correction. AVO analysis is repeated on the revised gathers and another residual velocity is calculated. This process is iterated until convergence occurs. This reduces the side effects mentioned above.

Velocities from seismic inversion. Usually, the term *seismic inversion* refers to transformation of poststack or prestack data into acoustic impedance. Because acoustic impedance is a layer property, it simplifies lithologic and stratigraphic identification and may be directly converted to lithologic or reservoir properties such as pseudo velocity, porosity, fluid fill, and net pay. For geopressure prediction, inversion can be implemented as a means to refine the velocity field beyond the resolution of residual velocity analysis, and also as a means to separate unwanted data from the pressure calculations.

The preferred methodology for implementing inversion for geopressure prediction is to start with a 3D residual velocity field (e.g., Figure 12) that can be used as a low-frequency velocity field to seed the inversion. The inversion is then used to refine the velocity field using the reflectivity information contained in the stacked data or gathers to provide the high-frequency velocity field.

As noted earlier, it is often observed during pressure prediction that certain layers violate the rules of the prediction process. Such layers, which include nonclastic rocks like carbonates and volcanics, coals, and marls, and reservoirs affected by hydrocarbon effects, essentially violate the premise of the pressure calibration because they have very different compaction behaviors from clean shales that are used to build a typical primary compaction curve. These layers are usually embedded in the seismic velocity field so that they can't be easily separated from the shales and sands that do follow the rules of the game. Let's consider a case where a shale section has multiple coal seams embedded in it

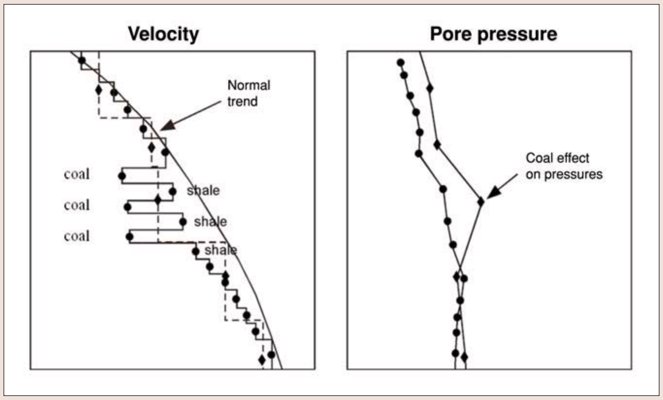

Figure 14. Comparison of stacking velocities (dashed line) and inversion velocities through a thinly bedded set of coal seams showing the improved resolution that inversion can provide (left), along with the difference in the resulting pore-pressure prediction caused by averaging through the coals (right) (after Huffman, 2002).

(Figure 14). In this situation, the seismic velocity field is too coarsely sampled in time to see the coals as separate layers as shown in the dashed velocity profile. When this velocity profile is used to predict pore pressure, the low-velocity coals cause an anomalously high pressure estimate that is false. The application of inversion in such an example (the solid velocity curve) allows the coals to be separated out from the shales by manually picking the coals for removal, or by using horizons to exclude the coals from the pressure calculation. In this case, the pressure prediction follows the shales properly and the prediction is correct. This concept can be applied to any exotic velocity effect from nonclastic rocks or for hydrocarbon effects in reservoirs.

Poststack inversion. Because the inversion process transforms seismic amplitudes directly into impedance values, special attention needs to be paid to their preservation, so that the observed amplitude variations are related to geologic effects. Thus, the seismic data should be free of multiples, acquisition imprint, have high S/N ratio, zero-offset migrated, and without any numerical artifacts. Several different techniques/methodologies are commonly used to perform acoustic impedance inversion. The prominent ones are recursive, blocky, sparse-spike, stratigraphic, and geostatistical inversion (Chopra and Kuhn, 2000). All these model-based inversion methods belong to a category called *local optimization methods*. A common characteristic is that they iteratively adjust the subsurface model in such a way that the misfit function (between synthetic and actual data) decreases monotonically. In the case of good well control, the starting model is good and so the local optimization methods produce satisfactory 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. In such cases, global optimization methods (e.g., simulated annealing) need to be used. Global optimization methods employ statistical techniques and give reasonably accurate results.

Thus, whatever inversion approach is adopted, the acoustic impedance volumes so generated have significant advantages that include increased frequency bandwidth, enhanced resolution and reliability of amplitude interpretation through detuning of seismic data, and obtaining a layer property that affords convenience in understanding and interpretation. However, the results are sometimes viewed with suspicion due to the inherent problem of uniqueness in terms of lithology and fluid discrimination. Variations in acoustic impedance could result from a combination of many factors like lithology, porosity, fluid content, and saturation or pore pressure. Prestack inversion helps in reducing this ambiguity, as it can generate not only compressional but shear information for the rocks under consideration.

Prestack inversion. The commonly used prestack inversion methods, aimed at detecting lithology and fluid content, derive the AVO intercept and AVO gradient (Shuey, 1985) or normal incident reflectivity and Poisson reflectivity (Verm and Hilterman, 1995) or P-and S- reflectivities (Fatti et al., 1994). Fatti's approach makes no assumption about the V_P/V_S and density and is valid for incident angles up to 50°. The AVO-derived reflectivities are usually inverted individually to determine rock properties for the respective rock layers. The accuracy and resolution of rock property estimates depend to a large extent on the inversion method utilized.

A joint or simultaneous inversion flow may simultaneously transform the P- and S- reflectivity data (Ma, 2001) into acoustic and shear impedances or it may simultaneously invert for rock properties starting from prestack P-wave offset seismic gathers (Ma, 2002). Simultaneous inversion methodology extracts an enhanced dynamic range of data from offset seismic stacks, resulting in an improved response for reservoir characterization over traditional poststack or AVO analysis (Fowler et al., 2002).

Prestack inversion for rock properties has been addressed lately using global optimization algorithms. In these model-driven inversion methods, synthetic data are generated using an initial subsurface model and compared to real seismic data; the model is modified, and synthetic data are updated and compared to the real data again. If after a number of iterations no further improvement is achieved, the updated model is the inversion result. Some constraints can be incorporated to reduce the nonuniqueness of the output. These methods utilize a Monte Carlo random approach and effectively find a global minimum without making assumptions about the shape of the objective function and are independent of the starting models.

Mallick (1999) presented a prestack inversion method using a genetic algorithm to find the P- and S- velocity models by minimizing the misfit between observed angle gathers and their synthetic computations. This method is computer intensive, but the superior quality of the results justifies the need for such an inversion.

The sonic and velocity log-derived porosity trends from offshore Ireland suggest overpressures within Tertiary shale sequences. Analysis of seismic velocities for this area suggest normal shale compaction for most of the Tertiary overburden, except in certain lithologies where overcompaction is seen. The stacking velocities were picked on a coarse grid and were not horizon consistent, so they look blocky as shown in Figure 15a. If there are lateral velocity variations, as seen in this case, this approach is not suitable for pore-pressure analysis. In order to obtain accurate and high resolution seismically derived velocities, several iterations of the prestack depth migration using tomography were attempted. The grid-based tomography provides an optimum seismic image as well as the velocity section shown in Figure 15b corresponding to Figure 15a. Next prestack seismic inversion was attempted using Ma's (2001) approach to be able to predict different lithologies in terms of P- and S- impedances and the two equivalent sections are shown in Figure 15c and d.

Terzaghi's effective principle (1943) was then used to

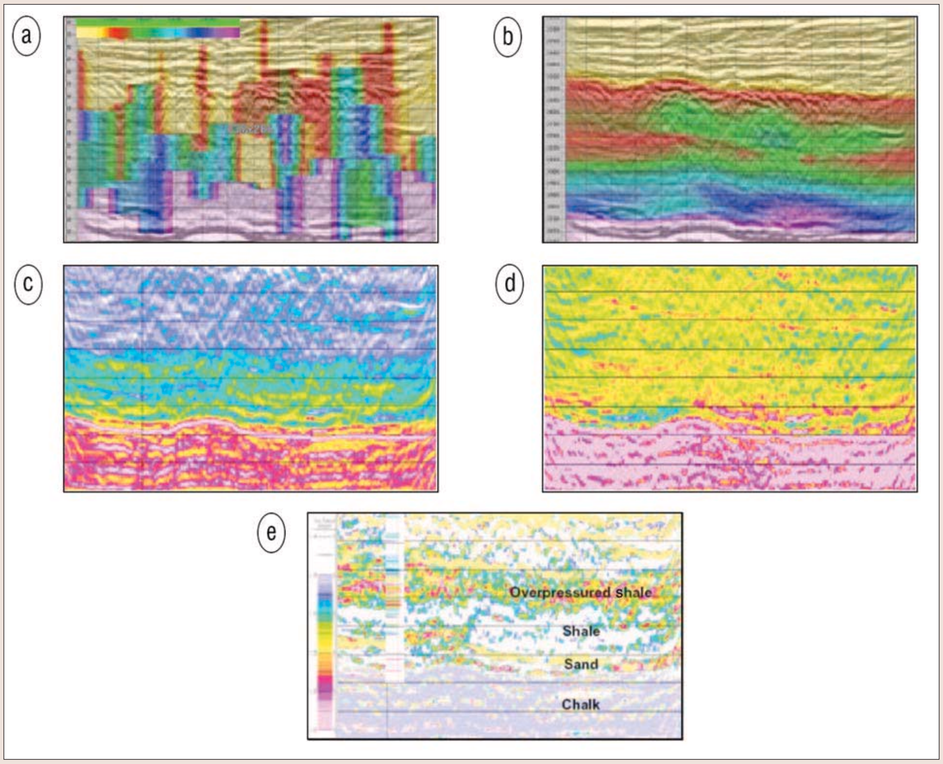

Figure 15. *Interval velocity section obtained with (a) traditional velocity picking and (b) using reflection tomography approach. (c) P-impedance section and (d) S-impedance section obtained with prestack joint inversion. (e) Pore-pressure gradient section obtained using Terzaghi's approach. Notice the overpressured shale zone running left to right (after Gordon et al., 2002).*

transform the seismic-inversion-derived impedance to pore pressure. The equivalent section shown in Figure 15e shows overpressured shales as anticipated in this area. Such information provides assurance for development well locations.

Discrepancies between wellbore and seismic velocities. One challenge in performing geopressure prediction with seismic velocities is that the seismic and wellbore velocities often do not calibrate properly against each other. When this occurs, an obvious question arises regarding which data type provides the best base calibration for geopressure. While this topic is beyond the general scope of this review, a few words should be said about this important topic. The issue not only affects the calibration for pressure but also has an impact on the time-depth conversion that is required to equate the seismic velocities in time to pressure profiles in depth that are used for drilling wells.

While sonic velocities provide the highest resolution of the available velocity data, they often don't provide the best calibration for seismic-based prediction because of differences in the frequency of measurement compared to seismic data and due to invasion and other deleterious wellbore effects. In many cases, the sonic and seismic can't be reconciled, which then requires that the seismic be used to calibrate directly to avoid a miscalibration when the jump is made from the sonic log to seismic data. In contrast, VSP and check-shot data are measured at the same frequency as the seismic data, but they provide a higher-resolution velocity field that can be calibrated to the sonic in depth as well. Consider the example in Figure 16. In this case, a seismic velocity function at a well location was compared to the check-shot survey and the sonic log from the well. On inspection, the interval from 1900 to 2300 m revealed a discrepancy between the sonic and the seismic velocities. Further inspection revealed that the check-shot data agreed with the sonic log from 1900 to 2150 m, but from 2150 to 2300 m, the check-shot agreed with the seismic velocity function. Note the impact that this discrepancy has on the pressure prediction. Such differences are commonplace, so addressing them is something that every pressure analyst will face. In this particular case, the discrepancy was easily explained. The upper zone from 1900 to 2150 m was a thick complex gas reservoir that affected the sonic log and the check-shot survey but was not detected by the seismic velocities. In contrast, the zone from 2150 to 2300 m was affected by severe invasion of the formation by drilling mud after the mud weight was raised to manage the gas kick in the zone above. This mud invasion, coupled with dispersion effects in the sonic log, conspired to make the sonic read too fast. In this case, advanced petrophysical corrections including dispersion and invasion corrections were able to correct the sonic log to match the seismic and check-shot data. Geopressure prediction requires sonic logs that have been fully corrected for environmental effects, and these corrections should be done rigorously when a well is to be used for pressure calibration. It is also important to recognize that these corrections in the velocity field, whether they be applied to sonic logs or to seismic velocities, will also affect the depth conversion from the seismic time domain to the depth domain. Therefore, it is worth taking the time to properly calibrate the sonic and seismic data with the check-shot and VSP data to assure that the pressure-prediction process is as robust as possible.

In most cases, the optimal work flow for geopressure involves calibration of the sonic with the check-shot or VSP data, and calibration of the seismic data to the same check-shot survey. This allows all of the velocity data sets to be corrected to the same basis using data acquired in the wellbore where the time-depth relationship is well defined. These corrections can be significant, and often can vary from one geologic interval to another. In particular, when unloading pressures are encountered in the subsurface, the deviation between the wellbore data and the seismic velocities can increase significantly, and this must be accounted for by more sophisticated methods of depth correction. For additional information on this topic, the reader is referred to the excellent paper on the subject by Bell (2002).

Conclusions. Conventional seismic velocities are sparse and do not allow for detailed velocity interpretation. Other methods like geologically consistent velocity analysis and horizon-keyed velocity analysis have been developed that serve to make velocity interpretation more meaningful and have enough resolution to significantly improve the quality of pore pressure determination. Reflection tomographic velocity analysis, residual velocity analysis, and velocity determination using poststack and prestack seismic simultaneous inversion hold promise as they have significantly improved

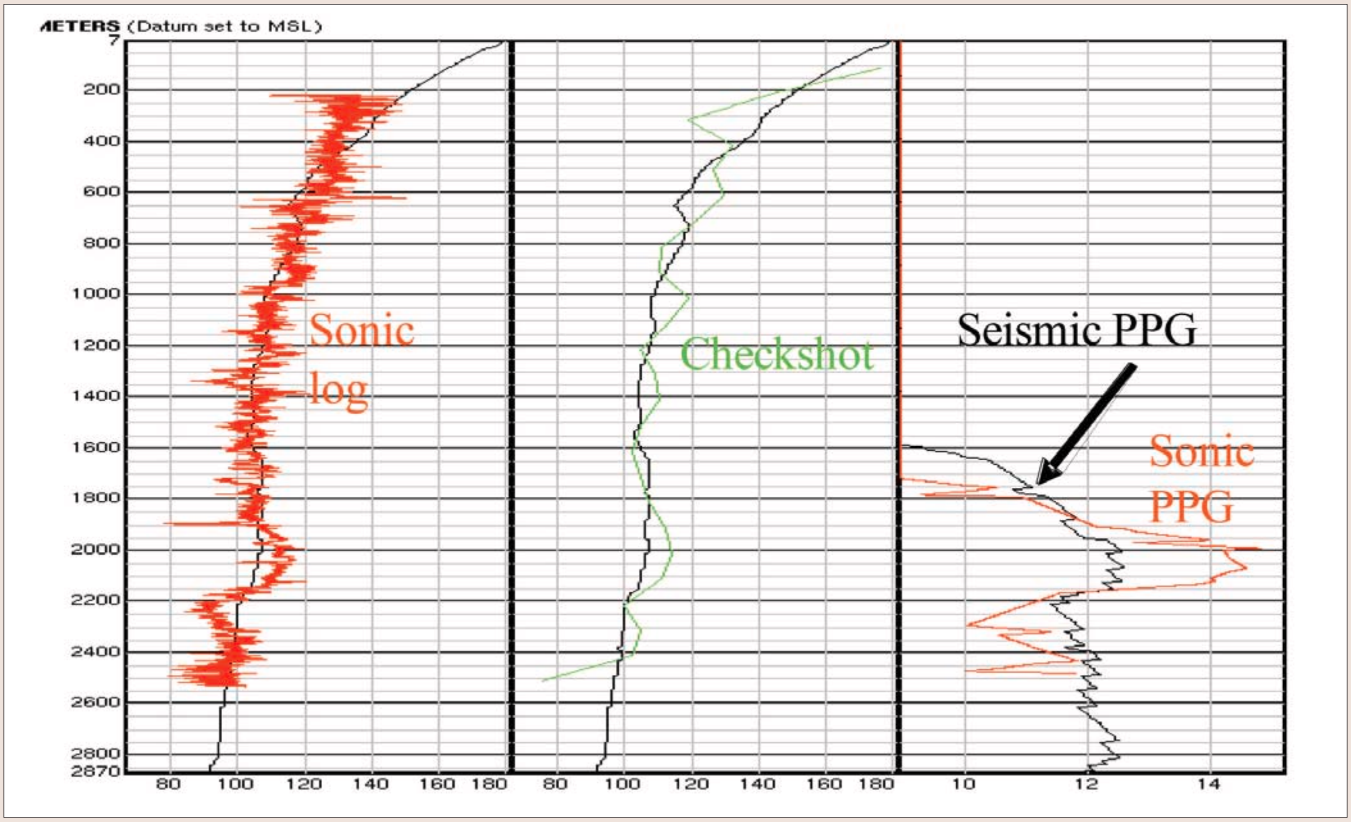

Figure 16. Example of mismatch between sonic log, check-shot, and seismic velocity data. The black curve in the left and center tracks is the seismic interval-velocity curve (after Huffman et al., 2003).

our ability to obtain accurate pore-pressure prediction from seismic data. However the choice of the most suitable velocity estimation methodology for a given area will depend on a number of factors requiring answers to questions like:

- Are we dealing with a structurally complex area? Is it possible to model velocity with vertical functions only or need to include lateral variation as well?
- Is the straight raypath assumption valid and can the velocity be modeled in time or depth?
- Is correction for anisotropy in the area compelling? What type of anisotropy?
- Are we looking for localized pressure anomalies or broader regional effects?
- Can the sands and shales be discriminated and does the velocity estimation technique being used also correlate with this?
- Are nonclastic rocks or hydrocarbon-bearing zones present in the data that require increased resolution to isolate them from the pressure prediction?

Answers to these questions will help the user choose the most appropriate velocity-estimation procedure and hence arrive at an effective pore-pressure prediction. Integration of accurate velocity information with petrophysical analysis can improve the velocity calibration among sonic logs, check-shot surveys, and seismic data that will directly impact the quality of the resulting pore-pressure prediction that is essential for improved risking of prospects and for planning of complex wells in difficult geologic environments.

Suggested reading. "Regional and high resolution 3D pore-pressure prediction in deep-water offshore West Africa" by Banik et al. (SEG 2003 *Expanded Abstracts*). "Velocity estimation for pore pressure prediction" by Bell (in *Pressure Regimes in Sedimentary Basins and Their Prediction, AAPG Memoir 76*, 2002). "Tomographic determination of velocity and depth in laterally varying media" by Bishop et al. (GEOPHYSICS, 1985). "Pressure estimation in a structurally complex regime—a case study from Macuspana Basin, Mexico" by Caudron et al. (SEG 2003 *Expanded Abstracts*). "Seismic inversion" by Chopra and Kuhn (CSEG *Recorder*, 2001). "Geologically consistently seismic processing velocities improve time to depth conversion" by Crabtree et al. (CSEG 2000 *Expanded Abstracts*). "Geopressure prediction using seismic data: current status and the road ahead" by Dutta (GEOPHYSICS, 2002). "Detection of gas in sandstone reservoirs using AVO analysis: a 3D seismic case history using the Geostack technique" by Fatti et al. (GEOPHYSICS, 1994). "Simultaneous inversion of the Ladybug prospect and derivation of a lithotype volume" by Fowler et al. (SEG 2000 *Expanded Abstracts*). "Shared knowledge and the challenge of abnormal pressure" by Gordon et al. (PETEX, 2002). "The future of pore-pressure prediction using geophysical methods" by Huffman (*TLE*, 2002). "Geopressure prediction advances in the Veracruz Basin, Mexico" by Huffman et al. (SEG 2003 *Expanded Abstracts*). "Synthetic sonic logs—a process for stratigraphic interpretation" by Lindseth (GEOPHYSICS, 1979). "Global joint inversion for the estimation of acoustic and shear impedances from AVO derived P- and S- wave reflectivity data" by Ma (*First Break*, 2001). "Simultaneous inversion of prestack seismic data for rock properties using simulated annealing" by Ma (GEOPHYSICS, 2002). "Some practical aspects of prestack waveform inversion using a genetic algorithm: An example from east Texas Woodbine gas sand" by Mallick (GEOPHYSICS, 1999). "Automated interval velocity inversion" by Mao et al. (SEG 2000 *Expanded Abstracts*). "Robust automatic continuous velocity analysis" by Ratcliff and Roberts (SEG 2003 *Expanded Abstracts*). "Seismic pore pressure prediction using reflection tomography and 4C seismic data" by Sayers et al. (*TLE*, 2002). "Nonlinear one-dimensional seismic waveform inversion using simulated annealing" by Sen and Stoffa (GEOPHYSICS, 1991). "A simplification of the Zoeppritz equations" by Shuey (GEOPHYSICS, 1985). "3D pore pressure prediction in the Columbus Basin, Offshore Trinidad & Tobago" by Snijder et al. (*First Break*, 2002). "Reflection tomography in the post migrated domain" by Stork (GEOPHYSICS, 1992). "Velocity estimation in complex chalk" by Sugrue et al. (CSEG 2004 *Expanded Abstracts*). "Velocities from amplitude variations with offset" by Swan (GEOPHYSICS, 2001). *Theoretical Soil Mechanics* by Terzaghi (John Wiley and Sons, Inc, 1943). "Lithology color-coded seismic sections: The calibration of AVO crossplotting to rock properties" by Verm and Hilterman (*TLE*, 1995). "Macrovelocity model estimation through model-based globally-optimised residual curvature analysis" by Wang et al. (SEG 1995 *Expanded Abstracts*). "Automated 3D tomographic velocity analysis of residual moveout in prestack depth migrated common image point gathers" by Woodward et al. (SEG 1998 *Expanded Abstracts*). *Seismic Data Analysis* by Yilmaz (SEG, 2001). "Tomographic velocity analysis in strongly anisotropic TTI media" by Zhou et al. (SEG 2004 *Expanded Abstracts*). TLE

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