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-
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-
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).
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
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).

**Refraction tomography.** Refraction 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
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
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 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.
Model-based inversion methods belong to a category called are recursive, blocky, sparse-spike, stratigraphic, and geo-
logic effects. Thus, the seismic data should be free of mul-
tiples, acquisition imprint, have high S/N ratio, zero-offset
velocities through a thinly bedded set of coal seams showing the improved
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 trans-
forms seismic amplitudes directly into impedance values,
special attention needs to be paid to their preservation, so
that the observed amplitude variations are related to geo-
logic effects. Thus, the seismic data should be free of mul-
tiples, acquisition imprint, have high S/N ratio, zero-offset
migrated, and without any numerical artifacts. Several dif-
ferent techniques/methodologies are commonly used to
analyze the data, and it is important to choose the appro-
propriate one for the specific application.

Variations in acoustic impedance could result from a com-
bination of many factors like lithology, porosity, fluid con-
tent, 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 con-
sideration.

Prestack inversion. The commonly used prestack inver-
sion methods, aimed at detecting lithology and fluid con-
tent, derive the AVO intercept and AVO gradient (Shuey,
1985) or normal incident reflectivity and Poisson reflectiv-
ity (Verm and Hilterman, 1995) or P-and S- reflectivities
(Fatti et al., 1994). Fatti’s approach makes no assumption
about the Vp/Vs 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 simultane-
ously transform the P- and S- reflectivity data (Ma, 2001)
to acoustic and shear impedances or it may simultaneously
invert for rock properties starting from prestack P-wave off-
set 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).

Poststack 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 seis-
mic data; the model is modified, and synthetic data are
updated and compared to the real data again. If after a num-
ber 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 assump-
tions about the shape of the objective function and are inde-
pendent of the starting models.

Mallick (1999) presented a prestack inversion method
using a genetic algorithm to find the P- and S-velocity mod-
els by minimizing the misfit between observed angle gath-
ers 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 sug-
gest normal shale compaction for most of the Tertiary over-
burden, 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 res-
olution seismically derived velocities, several iterations of
the prestack depth migration using tomography were
attempted. The grid-based tomography provides an opti-
mum 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
Inspection revealed that the check-shot data agreed with the sonic and the seismic velocities. Further, the interval from 1900 to 2300 m revealed a discrepancy between the sonic and the seismic velocities. Consider the example in Figure 16. In this case, a seismic survey and the sonic log from the well. On inspection, the time-depth conversion that is required to equate the sonic log to seismic data. This allows all of the velocity data sets to be transformed 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.

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...
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.


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**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).

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