

Borehole Acoustic Waves

Borehole acoustic waves may be as simple or as complex as the formations in which they propagate. An understanding of wave-propagation basics is essential for appreciation of modern sonic-logging technology.

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Everyday sounds come from many sources. Keyboards click, crickets chirp, telephones ring and people laugh. Understanding the information contained in these sounds is something that most people do without thinking. For most, deciphering the sounds they hear is much more important than knowing what sound waves are and how they travel.

However, for geoscientists and others who must understand the information contained in sound waves traveling in the Earth, it is essential to know what sound waves are and how they travel. This article reviews the basic types of acoustic sources and the sound waves that travel in rocks near a borehole. We also discuss the effects that variations in rock properties have on acoustic waves.

The acoustic waves recorded by a sonic-logging tool depend on the energy source, the path they take and the properties of the formation and the borehole. In wireline logging, there are two primary types of sources, monopole and dipole. A monopole transmitter emits energy equally in every direction away from its center, while a dipole transmitter emits energy in a preferred direction.

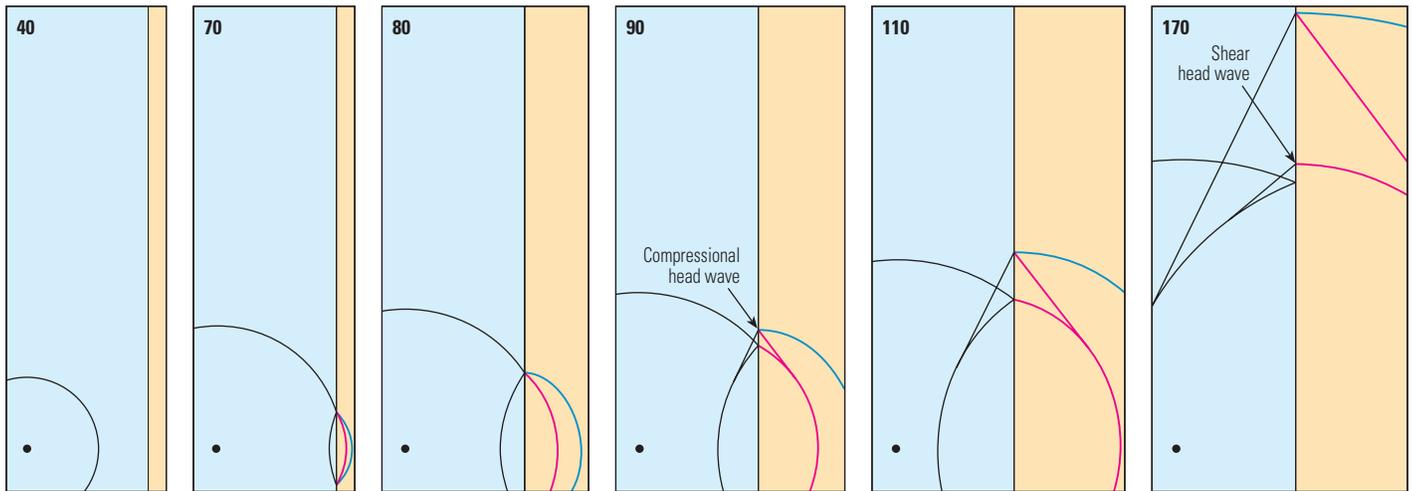
From a monopole transmitter located in the center of the borehole, a spherical wavefront travels a short distance through the borehole fluid until it meets the borehole wall. Part of the energy is reflected back into the borehole, and part of the energy causes waves to propagate in the formation ([next page, top](#)). The direction of wave propagation is always perpendicular to the

wavefront. This simple case also assumes the formation is homogeneous and isotropic, and that the sonic tool itself has no other effect on wave propagation.¹

The 3D cylindrical setting of the wellbore complicates this explanation, which can be simplified by examining a vertical plane through the axis of a vertical borehole. In the resulting 2D system, spherical wavefronts become circles and propagate in one plane. In a 3D world, wavefronts propagate everywhere outward from the source and surround the borehole symmetrically.

In the 2D simplification, when the wavefront in the borehole mud meets the borehole wall, it generates three new wavefronts. A reflected wavefront returns toward the borehole center at speed V_m . Compressional, P -, and shear, S -, waves are transmitted, or refracted, through the interface and travel in the formation at speeds V_p and V_s , respectively. In this simplest case of a hard, or fast, formation, $V_p > V_s > V_m$.

Once the refracted P -wave becomes parallel to the borehole wall, it propagates along the borehole-formation interface at speed V_p , faster than the reflected borehole-fluid wave. According to Huygens principle, every point on an interface excited by a P -wave acts as a secondary source of P -waves in the borehole as well as P - and S -waves in the formation. The combination of these secondary waves in the borehole creates a new linear wavefront called a head wave.² This first head wave in the mud is known as the compressional head wave, and its



^ The first few moments of simplified wavefront propagation from a monopole transmitter in a fluid-filled borehole (blue) and a fast formation (tan). Both media are assumed homogeneous and isotropic. Tool effects are neglected. Time progression is to the right. Numbers in the upper left corner correspond to time in μs after the source has fired. Wavefronts in the mud are black, compressional wavefronts in the formation are blue, and shear wavefronts in the formation are red. The compressional head wave can be seen at 90 μs , and the shear head wave can be seen at 170 μs .

arrival at the receivers is recorded as the P arrival. The P -wave takes longer to arrive at receivers that are farther from the source. The time difference between P arrivals divided by the distance traveled is known as Δt , or slowness, and is the reciprocal of speed. This is the most basic sonic-logging measurement.³

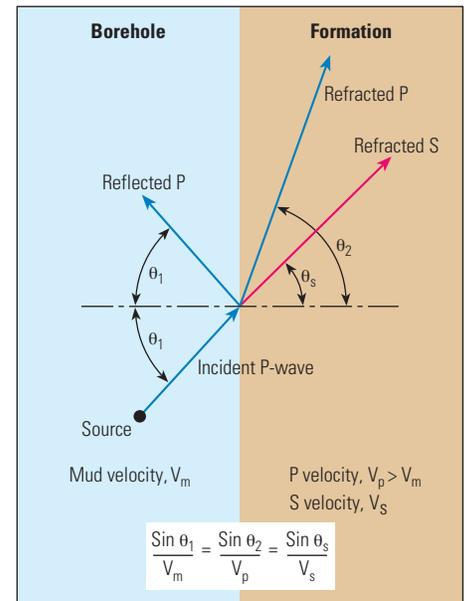
The P -wave that continues into the formation is known as a body wave, and travels on deeper into the formation unless a reflector sends it back toward the borehole, at which time it is called a reflected P -wave. Standard sonic logging ignores reflected P -waves, but special applications, such as those described near the end of this article, take advantage of the extra information contained in reflected P -waves.

The behavior of refracted S -waves is similar to that of refracted P -waves. When the refracted S -wave becomes parallel to the borehole wall, it propagates along the borehole-formation interface as a shear disturbance at speed V_s and generates another head wave in the borehole fluid. Its arrival at the receivers is recorded as the S -wave. In this way, shear slowness of a fast formation can be measured by a tool surrounded by borehole fluid, even though S -waves cannot propagate through the fluid.

In cases when the shear-wave speed is less than the mud-wave speed—a situation known as a slow formation—the shear wavefront in the formation never forms a right angle with the borehole. No shear head wave develops in the fluid. In both fast and slow formations, an S body wave continues into the formation.

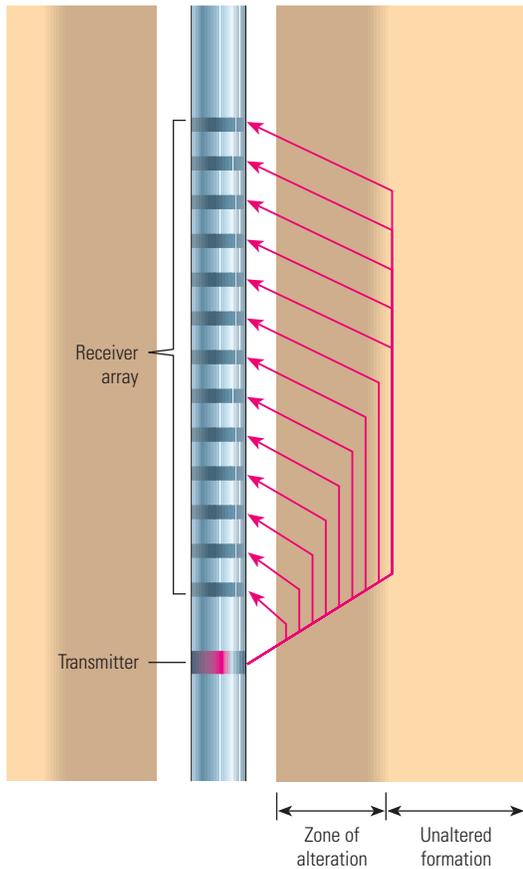
Another way of visualizing how P and S head waves travel near the borehole is through ray tracing. Strictly speaking, ray tracing is valid only when the wavelength is much smaller than the diameter of the borehole, or when the wavefronts can be approximated as planes rather than spheres or cones. Most borehole acoustic modes, especially those at low frequencies, do not meet these conditions, but ray tracing can still be useful for visualization. A ray is simply a line perpendicular to a wavefront, showing the direction of travel. A raypath between two points indicates the fastest travel path. Changes in raypath occur at interfaces and follow Snell's law, an equation that relates the angles at which rays travel on either side of an interface to their wave speeds (right). Among other things, Snell's law explains the conditions under which head waves form and why none form in slow formations.

Ray tracing is useful for understanding where waves travel and for modeling basics of sonic-tool design, such as determining the transmitter-receiver (TR) spacing that is required to ensure that the formation path is faster than the direct mud path for typical borehole sizes and formation P and S velocities. This ensures that the tool will measure formation properties rather than borehole-mud properties. Ray tracing also helps describe the relationship between TR



^ Wavefront reflection and refraction at interfaces, and Snell's law. θ_1 is the angle of incident and reflected P -waves. θ_2 is the angle of refracted P -waves. θ_s is the angle of refracted S -waves. V_m is mud-wave velocity. V_p is P -wave velocity in the formation, and V_s is S -wave velocity in the formation. When the angle of refraction equals 90° , a head wave is created.

1. A homogeneous formation is one with uniform velocity. In other words, the velocity is independent of location. An isotropic formation is one with velocity independent of direction of propagation.
2. The head wave has a conical wavefront in 3D.
3. Slowness typically has units of $\mu\text{s}/\text{ft}$.



^ Ray tracing using Snell's law to model raypaths. Here, rays are traced through a formation that has radially varying velocity in a zone of alteration. Velocity is lower near the borehole and grows larger with distance, a situation that arises when drilling induces near-wellbore damage. Rays traveling to the receivers nearest the transmitter travel only through the altered zone (dark brown), and rays traveling to distant receivers sense the velocity of the unaltered formation (light brown).

spacing and near-wellbore altered-zone thickness and velocity contrast (above). In addition, ray tracing is used in inversion techniques such as tomographic reconstruction, which solves for slowness models given arrival-time information.

After the *P* and *S* head waves, the next waves to arrive at the receivers from a monopole source are the direct and reflected mud waves. These are followed by trapped modes and interface waves that owe their existence to the cylindrical nature of the borehole. Trapped modes arise from multiple internal reflections inside the borehole. Wavefronts of particular wavelengths bouncing between the walls of the borehole interfere with each other constructively and produce a series of resonances, or normal modes. Trapped modes are not always seen on logs and may be affected by borehole condition. In slow formations, trapped modes lose part of their energy to the formation in the form of waves that

radiate into the formation. These are called leaky modes, and propagate at speeds between *P* and *S* velocities. Leaky modes are dispersive, meaning their different frequency components travel at different speeds.

Stoneley Waves

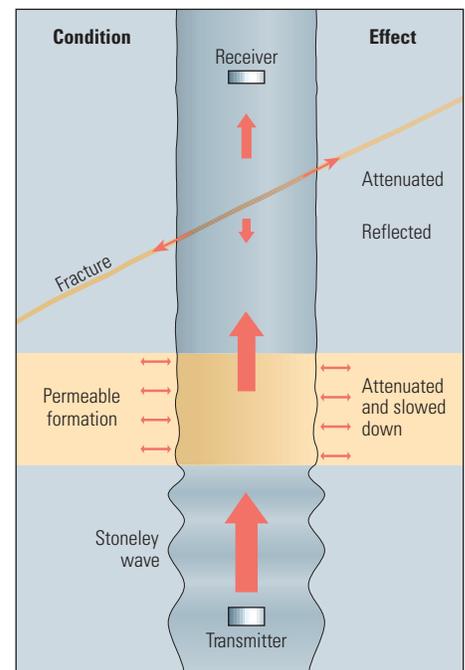
The last arrivals from a monopole source are interface, or surface, waves. Surface waves were first suggested by Lord Rayleigh in 1885.⁴ He investigated the response at the planar surface of an elastic material in contact with a vacuum and found that a wave propagated along the surface with particle motion that decreased in amplitude with distance from the surface—a property called evanescence. Rayleigh's findings predicted the existence of waves that propagate along the Earth's surface and give rise to the devastating shaking caused by earthquakes. The

same effect at a much smaller scale leads to “ground roll” noise in surface seismic surveys.

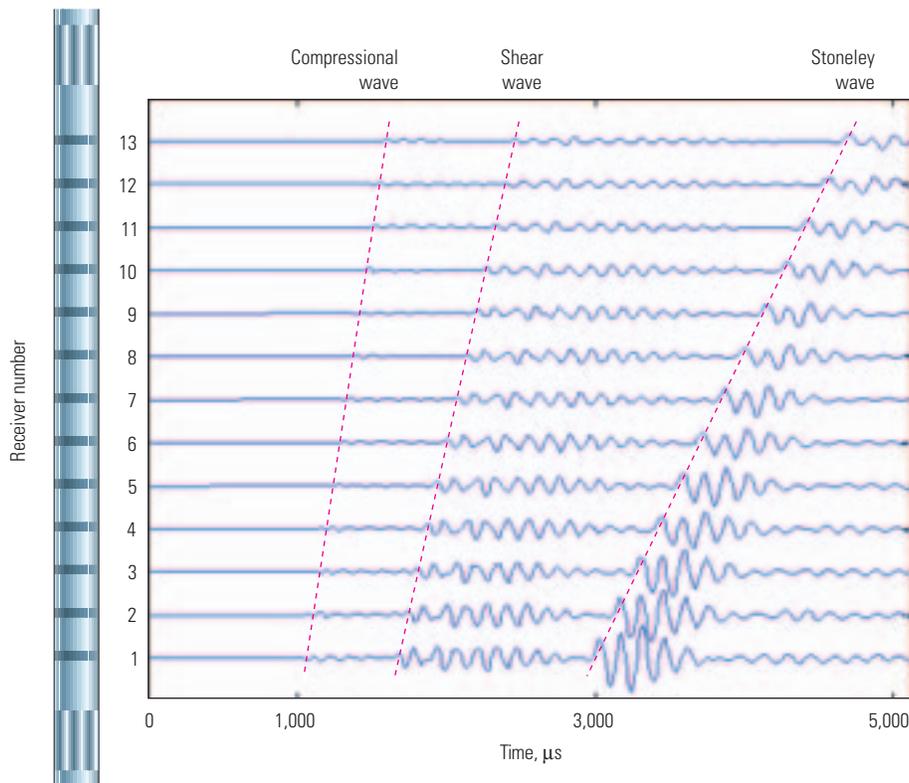
In 1924, Stoneley looked at waves propagating at the interface between two solids and found a similar type of surface wave.⁵ The particular case corresponding to a fluid-filled borehole, that is, the interface between a solid and a liquid, was described not by Stoneley, but by Scholte.⁶ The waves traveling at the fluid-borehole interface are nonetheless known as Stoneley waves. In other areas of geophysics, such as marine seismic surveys, waves traveling at a fluid-solid interface are called Scholte or Scholte-Stoneley waves.⁷

A Stoneley wave appears in nearly every monopole sonic log. Its speed is slower than the shear- and mud-wave speeds, and it is slightly dispersive, so different frequencies propagate at different speeds.

The decay of Stoneley-wave amplitude with distance from the interface is also frequency-dependent; at high frequencies, the amplitude decays rapidly with distance from the borehole wall. However, at low frequencies—or at wave-



^ The Stoneley wave, traveling at the interface between the borehole and the formation. The Stoneley wave is dispersive and its particle motion is symmetric about the borehole axis. At low frequencies, the Stoneley wave is sensitive to formation permeability. Waves traveling past permeable fractures and formations lose fluid, and viscous dissipation causes attenuation of wave amplitude and an increase in wave slowness. At open fractures, Stoneley waves are both reflected and attenuated. Red arrows in the center of the borehole symbolize Stoneley-wave amplitude.



^ Typical waveforms from a monopole transmitter in a fast formation, showing compressional, shear and Stoneley waves. The pink dashed lines are arrival times. A sonic-logging tool receiver array is shown at left.

lengths comparable to the borehole diameter—the Stoneley amplitude decays very little with distance from the borehole wall. At sufficiently low frequencies, the amplitude is nearly constant from one side of the borehole to the other, creating what is known as a tube wave. An example of a tube wave is the water-hammer effect that can sometimes be heard in plumbing pipes when flow is suddenly disrupted.

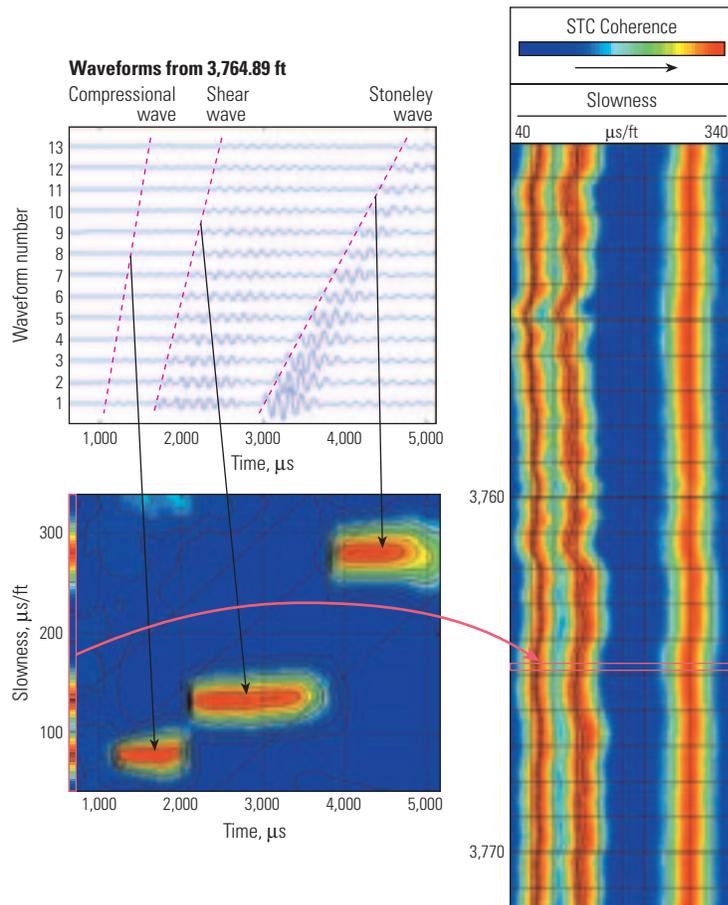
The low-frequency Stoneley wave is sensitive to formation permeability. When the wave encounters permeable fractures or formations, the fluid vibrates relative to the solid, causing viscous dissipation in these zones, which attenuates the wave and slows it down (previous page, right). The reductions in Stoneley-wave energy level and velocity vary with wave frequency. Stoneley-wave dispersion data over a wide bandwidth of frequencies can be inverted to estimate formation permeability.⁹ Open fractures can also cause Stoneley waves to reflect back toward the transmitter. The ratio of reflected to incident energy correlates with fracture aperture, or openness. This technique for the detection of permeable fractures works well in hard formations.⁹

All of the above waves propagate symmetrically up and down the borehole, and can be detected by monopole receivers—typically hydrophones. Hydrophones are sensitive to pressure changes in the borehole fluid, and have omnidirectional response, meaning that they respond equally to pressure changes from any direction.

Waveforms recorded at a given depth are initially displayed as a time series from the array of receivers (above). In some recordings, the

P-, *S*- and Stoneley-wave arrival times can be seen clearly, but often, data-processing techniques are used to pick times accurately. The difference in arrival times divided by the distance between receivers yields the slowness for each mode. However, in many recordings, high noise levels, bad hole conditions or other factors can cause these arrivals to be indistinct or mixed with each other. In such cases, visual or automated picking of arrival times fails to yield true slownesses.

4. Strutt JW, 3rd Baron Rayleigh: "On Waves Propagated Along the Plane Surface of an Elastic Solid," *Proceedings of the London Mathematical Society* 17 (1885): 4.
Rayleigh waves on the Earth's surface have vertical and horizontal components of motion. Other surface waves discovered by A.E.H. Love have two horizontal motion components.
5. Stoneley R: "Elastic Waves at the Surface of Separation of Two Solids," *Proceedings of the Royal Society, Series A* 106 (1924): 416–428.
6. Scholte JG: "On the Large Displacements Commonly Regarded as Caused by Love Waves and Similar Dispersive Surface Waves," *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen* 51 (1948): 533–543.
7. Bohlen T, Kugler S, Klein G and Theilen F: "Case History 1.5D Inversion of Lateral Variation of Scholte-Wave Dispersion," *Geophysics* 69, no. 2 (March–April 2004): 330–344.
8. Winkler KW, Liu HL and Johnson DJ: "Permeability and Borehole Stoneley Waves: Comparison Between Experiment and Theory," *Geophysics* 54, no. 1 (January 1989): 66–75.
9. Hornby BE, Johnson DL, Winkler KW and Plumb RA: "Fracture Evaluation Using Reflected Stoneley Wave Arrivals," *Geophysics* 54, no. 10 (October 1989): 1274–1288.



▲ Slowness-time-coherence (STC) processing for monopole arrivals. Waveforms at a given depth (*top left*) are scanned over time windows and over a range of angles—called moveouts, which are related to slowness. When the signals on the waveforms within the window are best correlated, coherence is maximum. An STC plot for that depth (*bottom left*) displays color-coded coherence in the slowness-time plane, with maximum coherence in red. The coherence values are projected onto a vertical strip along the slowness axis and then displayed as a thin horizontal strip at the appropriate depth on the STC projection log (*right*). A slowness log for each wave is generated by joining the coherence maxima at all depths.

Slownesses can be estimated in a robust way with minimal human intervention using a signal-processing technique that looks for similarity—known mathematically as semblance, or coherence—in waveforms across the receiver array.¹⁰ The method starts with an assumed arrival time and slowness for each wave type and searches the set of waveforms for the time and slowness that maximize coherence. The graph of coherence for different values of slowness and time is called a slowness-time-coherence (STC) plot, from which local maxima of the coherence contours can be identified (*above*). Maxima

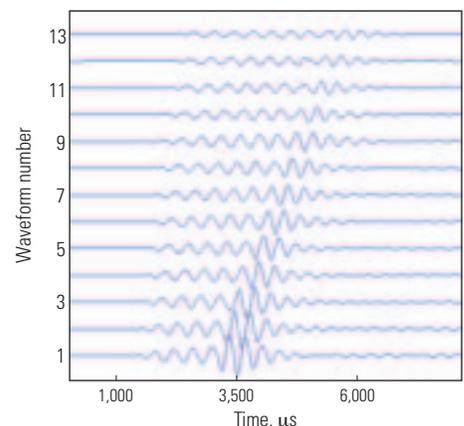
corresponding to compressional, shear and Stoneley slownesses plotted for each depth create a slowness log. The two dimensions of an STC plot are compressed into a single dimension by projecting the coherence peaks onto the slowness axis. This vertical strip of color-coded coherences, when plotted horizontally at the appropriate depth, forms an element of an STC-projection log, a standard sonic-logging output. The slowness of each mode is plotted on top of the STC projection.

Dipole Sources

So far, the discussion has focused on waves generated by monopole sources, but for some applications, a different type of source is required. For example, in slow formations, where monopole sources cannot excite shear waves, a dipole source can be effective. The dipole source primarily excites flexural waves, along with compressional and shear head waves. The motion of a flexural wave along the borehole can be thought of as similar to the disturbance that travels up a tree when someone standing on the ground shakes the tree trunk. The analogy works better if the tree trunk is fixed at the top and has constant diameter.

Typically, a tool designed to generate flexural waves will contain two dipole sources oriented orthogonally along the tool X- and Y-axes. The dipole transmitters are fired separately. First, the X-dipole is fired, and a flexural waveform is recorded. Then, the Y-dipole is fired, and a separate measurement is taken. The flexural wave travels along the borehole in the plane of the dipole source that generated it. The particle motion of the flexural wave is perpendicular to the direction of wave propagation, similar to S-waves, and flexural-wave slowness is related to S-wave slowness. Extracting S-wave slowness from flexural-wave data is a multistep process.

Flexural waves are dispersive, meaning their slowness varies with frequency (*below*). In many sets of flexural waveforms, it is possible to see the wave shape change across the receiver array as different frequency components propagate at different speeds. Because the wave shape



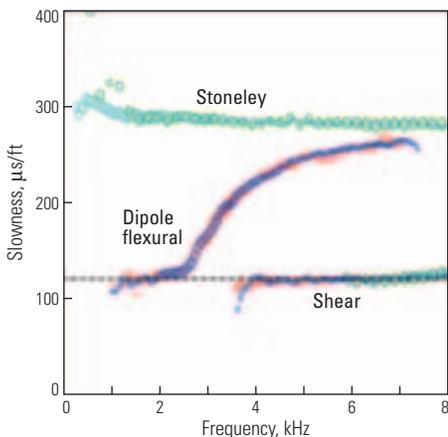
▲ Flexural-mode waveforms, showing a change in wave shape across the receiver array. In this case, the wave shape stretches out in time from near receiver (*bottom*) to far receiver (*top*). The change in wave shape is caused by dispersion.

changes across the receiver array, standard methods for estimating slowness, such as STC processing, which relies on wave-shape similarity, must be adapted to handle dispersive waves. Dispersive STC processing identifies the slowness of individual frequency components.¹¹

A plot of flexural-wave slowness versus frequency is called a dispersion curve (below). Dispersion-curve analysis compares modeled acoustic dispersion curves for homogeneous isotropic formations with curves measured by borehole sonic tools.¹²

The radial depth of investigation of flexural waves is approximately one wavelength. Low-frequency flexural waves probe deep into the formation, and high-frequency flexural waves have shallower depths of investigation. Analysis of flexural-mode slowness as a function of frequency can therefore provide detailed information about the formation near and far from the borehole.

At zero frequency, flexural-wave slowness is the true formation shear slowness. Plotting flexural-wave slowness versus frequency and identifying the zero-frequency limit of the curve allow estimation of formation shear slowness. In this way, analysis of flexural-wave dispersion allows estimation of shear slowness in fast or slow formations.¹³



^ Dispersion curves characterizing slowness at different frequencies in an isotropic formation. Shear waves are not dispersive; all their frequency components travel at the same slowness. Stoneley waves are only slightly dispersive. Flexural modes excited by a dipole source exhibit large dispersion in this formation. At the zero-frequency limit, flexural-wave slowness tends to the shear-wave slowness (dotted line).

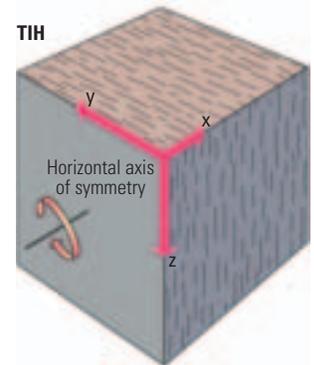
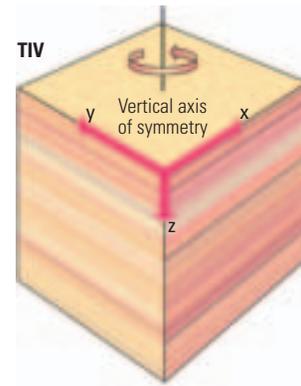
Up to now, this article has concentrated on the simplest case of a homogeneous isotropic formation and monopole and dipole sources. Such a formation has one *P*-wave slowness, one Stoneley-wave slowness and one *S*-wave slowness. Most of the applications for using sonic-logging results to infer formation porosity, permeability, fluid type, elastic moduli, lithology or mineralogy have been developed for homogeneous isotropic formations. Additional complexities arise in inhomogeneous or anisotropic formations. The rest of this article addresses anisotropy first, then looks at inhomogeneous formations.

Anisotropy

The spatial alignment of mineral grains, layers, fractures or stress causes wave velocity to vary with direction, a property called anisotropy.¹⁴ In seismic surveys, the anisotropy of the overburden shales is known to cause imaging difficulties that need to be corrected to place reservoir targets at the correct location. Information about anisotropy is also needed whenever an understanding of rock mechanics is required. Directional drilling, drilling in tectonically active areas, designing oriented-perforating jobs, planning hydraulic-fracturing operations and developing pressure-supported recovery plans all benefit from knowledge of elastic anisotropy.

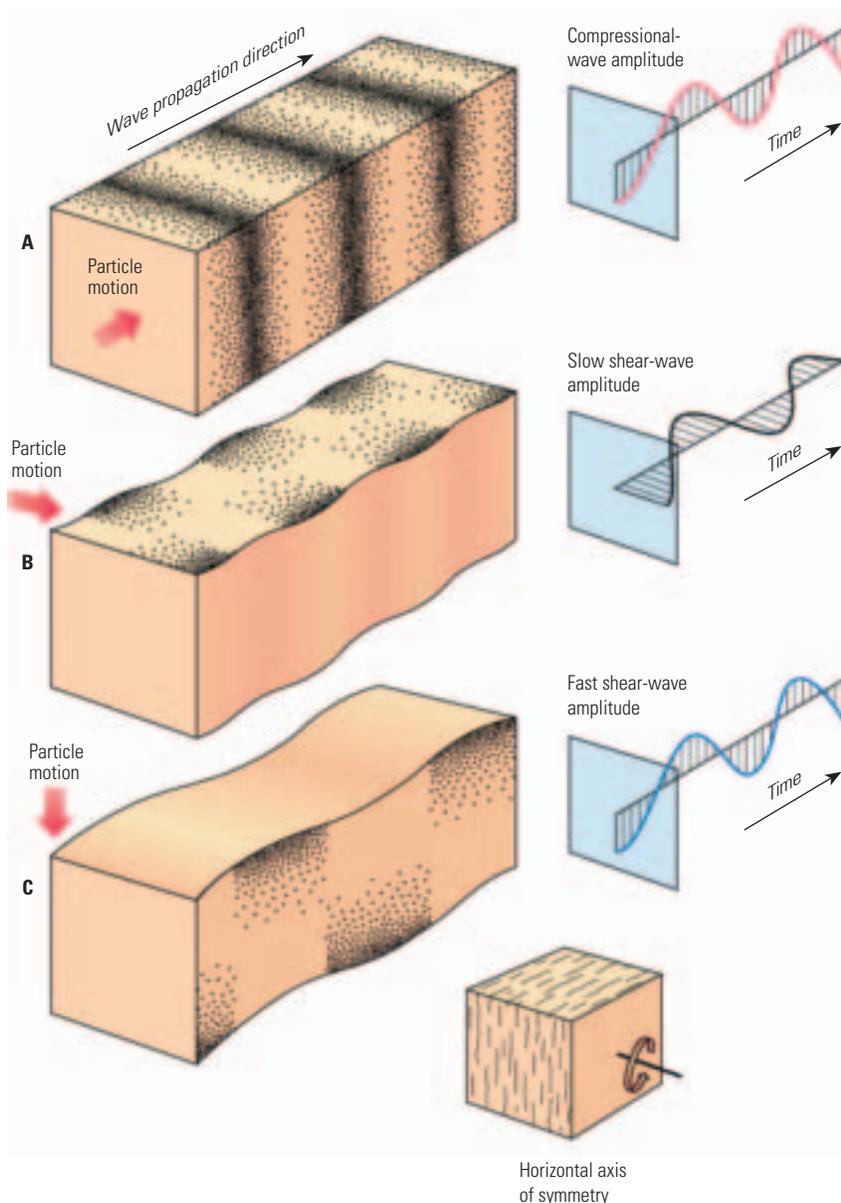
The natural processes that cause anisotropy also cause it to have one of two main orientations: horizontal or vertical. To a first approximation, horizontal layers create an anisotropic medium that may be considered isotropic in all horizontal directions, but anisotropic vertically. Such a medium is known as transversely isotropic with a vertical axis of symmetry (TIV) (above right). Similarly, vertical fractures create a simplified anisotropic medium that may be considered isotropic in any direction aligned with fracture planes, and anisotropic in the direction orthogonal to fracture planes. This medium is known as transversely isotropic with a horizontal axis of symmetry (TIH).

Sonic waves are sensitive to these directional differences in material properties. Waves travel fastest when the direction of particle motion, called polarization, is parallel to the direction of greatest stiffness. Compressional waves have particle motion in the direction of propagation, so *P*-waves travel fastest in directions parallel to layering and fractures, and travel more slowly when perpendicular to layering and fractures.



^ Simplified geometries in elastic anisotropy. In horizontal layers (top), elastic properties may be uniform horizontally, but vary vertically. Such a medium may be approximated as transversely isotropic with a vertical axis of symmetry (TIV), meaning that the formation may be rotated about the axis to produce a medium with the same properties. In formations with vertical fractures (bottom), elastic properties may be uniform in vertical planes parallel to the fractures, but may vary in the perpendicular direction. This medium may be approximated as transversely isotropic with a horizontal axis of symmetry (TIH).

10. Kimball CV and Marzetta TL: "Semblance Processing of Borehole Acoustic Array Data," *Geophysics* 49, no. 3 (March 1984): 274–281.
11. Kimball CV: "Shear Slowness Measurement by Dispersive Processing of the Borehole Flexural Mode," *Geophysics* 63, no. 2 (March–April 1998): 337–344.
12. Murray D, Plona T and Valero H-P: "Case Study of Borehole Sonic Dispersion Curve Analysis," *Transactions of the SPWLA 45th Annual Logging Symposium*, June 6–9, 2004, Noordwijk, The Netherlands, paper BB.
The key parameters required for dispersion-curve modeling are formation slowness, formation density, borehole-fluid velocity, borehole-fluid density and borehole diameter.
13. Sinha BK and Zeroug S: "Geophysical Prospecting Using Sonics and Ultrasonics," in Webster JG (ed): *Wiley Encyclopedia of Electrical and Electronic Engineers* Vol. 8. New York City: John Wiley and Sons, Inc. (1999): 340–365.
14. This holds for alignments on scales that are smaller than the wavelength of the waves in question.
Armstrong P, Ireson D, Chmela B, Dodds K, Esmersoy C, Miller D, Hornby B, Sayers C, Schoenberg M, Leaney S and Lynn H: "The Promise of Elastic Anisotropy," *Oilfield Review* 6, no. 4 (October 1994): 36–47.

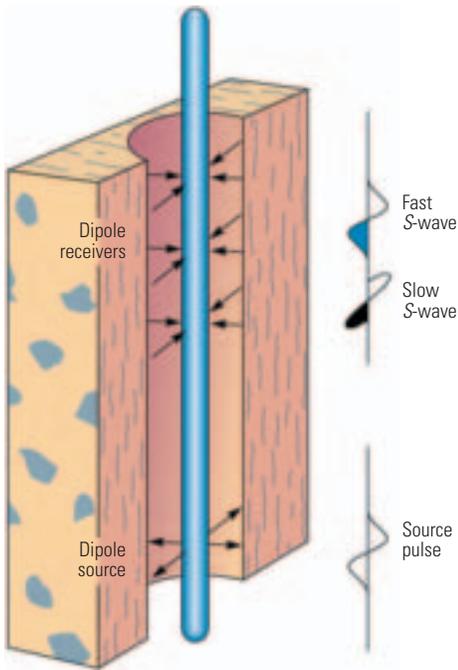


^ Particle motion and direction of propagation in compressional and shear waves. Compressional waves (A) have particle motion in the direction of wave propagation. Shear waves have particle motion orthogonal to the direction of propagation. In a TIH anisotropic material (*bottom*), a shear wave propagating parallel to fractures splits. The *S*-wave with vertically polarized particle motion, parallel to the fractures (C) is faster than the *S*-wave with particle motion polarized orthogonal to fractures (B).

Shear waves have particle motion perpendicular to the direction of propagation (*above*). In isotropic media, *S*-wave particle motion is contained in the plane containing the *P* and *S* raypaths. In anisotropic media, an *S*-wave will split into two shear waves with different polarizations and different velocities. The *S*-wave polarized parallel to the layering or

fractures is faster than the *S*-wave polarized orthogonal to layering or fractures. Flexural waves behave like *S*-waves, and so they split in the same ways. In the discussion that follows, *S*-waves and flexural waves are used interchangeably.

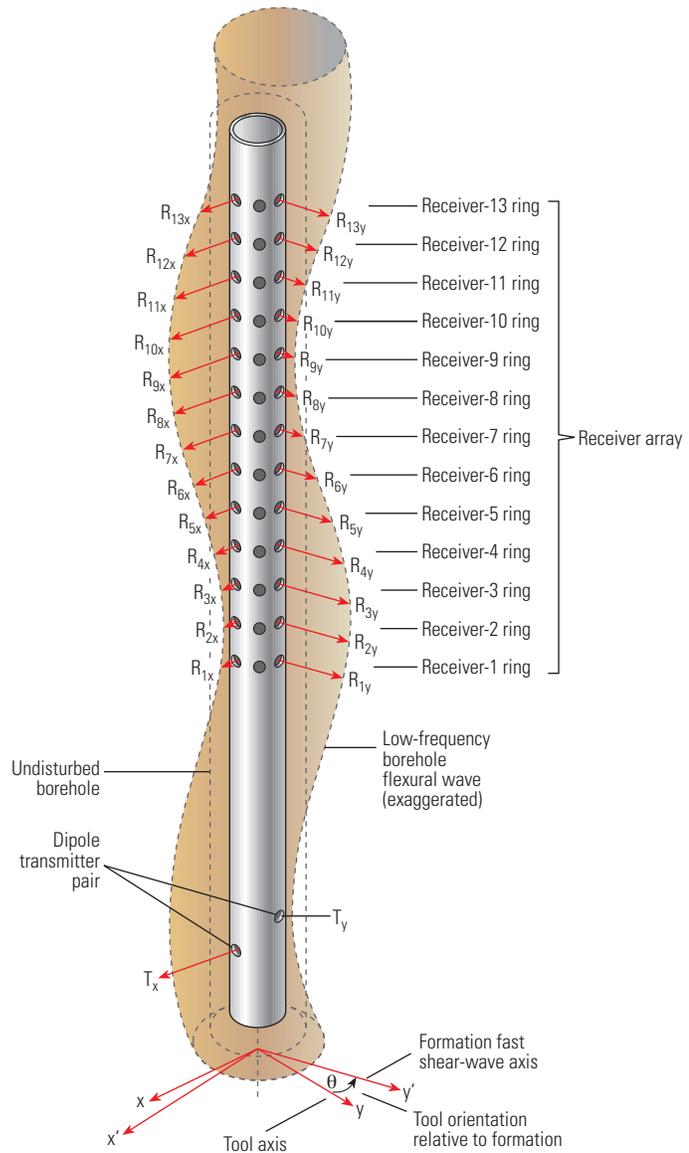
Sonic logging can be used to detect and quantify the direction and magnitude of anisotropy if the tool geometry and the anisotropy axis are properly aligned. In a TIH medium, such as a formation with aligned vertical fractures, *S*-waves propagating along a vertical borehole split into two waves, and the fast wave is polarized in the plane of the



^ Shear-wave splitting in a vertical borehole in a TIH medium with vertical fractures. No matter how the dipole source is oriented relative to the fast and slow directions of the medium, the shear wave will split into fast and slow components. The fast component aligns parallel to the plane of the fractures, while the slow component aligns perpendicular to the plane of the fractures.

fractures (above). Similarly, in a TIV medium, such as a shale or a finely layered interval, *S*-waves propagating in a horizontal borehole split, and the fast wave becomes polarized in the bedding plane.

The polarization of *S*-waves split by anisotropy cannot be detected by a single monopole receiver. Directional receivers are required. A suitable directional receiver can be created by substituting a single monopole receiver with two or more pairs of monopole receivers. Each pair of monopole receivers acts as a dipole receiver. For adequate recording of flexural waves, at least one dipole receiver is aligned with each dipole transmitter. At each firing of the dipole source, signals are recorded by the dipole receiver oriented "inline" with that source and also by the dipole receiver oriented "offline" (above right).¹⁵ This example shows recording of flexural waves at 13 receiver stations with eight receivers distributed in a ring at each station.¹⁶



^ Inline and offline response on azimuthally distributed receivers from a borehole flexural wave in an anisotropic formation. The flexural wave was excited by firing of the X-dipole transmitter, T_x , shown at the bottom. In this TIH medium, the flexural wave splits into fast and slow waves with components of particle motion on all receivers, not just those aligned with the tool X-axis.

In isotropic formations, flexural waves generated by a dipole source remain polarized in the plane of the source and are detected only on the dipole receiver aligned in that plane. However, in anisotropic formations, the flexural wave splits into fast and slow components aligned with the formation anisotropy. Unless the tool axes are fortuitously aligned with the

formation's fast and slow directions, flexural-wave energy will be recorded by the offline as well as the inline receivers.

The directions, or azimuths, of fast and slow shear or flexural waves can be seen in a crossed-dipole log. Creating a crossed-dipole log is a multistep process. The first step is decomposition and recombination of the waveforms

15. Offline is sometimes referred to as crossline.

16. Pistre V, Kinoshita T, Endo T, Schilling K, Pabon J, Sinha B, Plona T, Ikegami T and Johnson D: "A Modular Wireline Sonic Tool for Measurements of 3D (Azimuthal,

Radial, and Axial) Formation Acoustic Properties," *Transactions of the SPWLA 46th Annual Logging Symposium*, New Orleans, June 26-29, 2005, paper P.

acquired on all sensors at each receiver station to yield four waveforms corresponding to the inline and offline responses at every depth to the two orthogonal dipole transmitters. Next, these waveforms are mathematically rotated to put them in a coordinate system consistent with the directions of maximum and minimum offline waveform energy.¹⁷ Then, the waveforms corresponding to fast- and slow-shear orientations undergo semblance processing to obtain the fast and slow shear-wave slownesses.¹⁸ Zones with equal fast and slow shear-wave slownesses are isotropic, while zones with large differences between fast and slow shear-wave slownesses are highly anisotropic.

The slownesses of the fast and slow *S*-waves and the *P*- and Stoneley waves—the four slownesses that can be measured by sonic logging in an anisotropic medium—are transformed into four anisotropic moduli. These four moduli can almost characterize the simplest of anisotropic media. TIV and TIH media require five moduli to

be fully characterized. For more complex types of anisotropy, more measurements are required, such as *P*-waves propagating in different azimuths or inclinations, or *S*-waves traveling vertically and horizontally. Surface seismic and borehole seismic surveys often can provide this information.

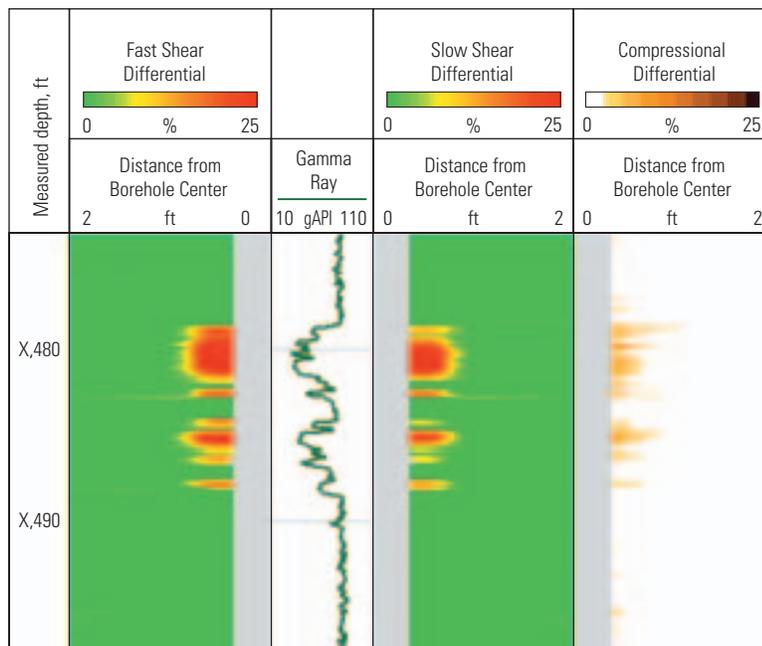
Inhomogeneity

Formation properties may vary not only with measurement direction, as in anisotropic formations, but also from place to place, in what are called inhomogeneous, or equivalently, heterogeneous, formations. As with anisotropy, detecting and quantifying inhomogeneity using acoustic waves will depend on the type of formation variation and its geometry relative to the borehole axis.

Standard sonic logging can characterize formation properties that vary along the borehole. Early sonic-logging tools run in vertical

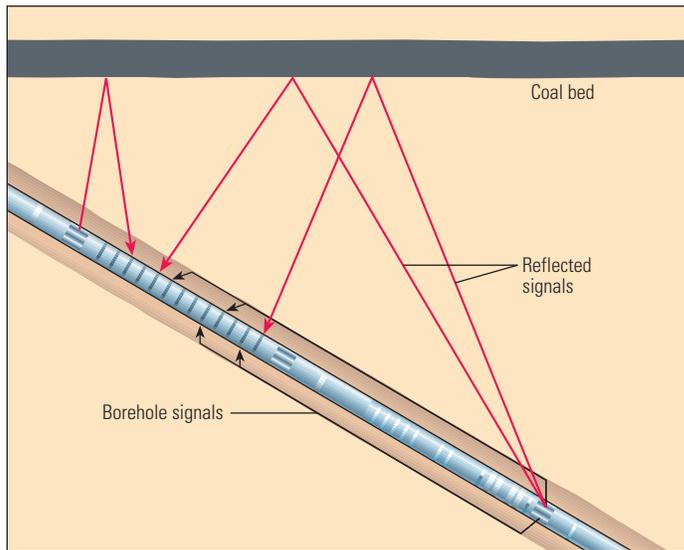
boreholes identified inhomogeneities in the form of boundaries between horizontal layers (see “History of Wireline Sonic Logging,” page 32). Other heterogeneities, such as high-permeability zones or open fractures that intersect the borehole, can be detected using Stoneley waves, as described earlier.

Formation properties that vary away from the borehole, or along the radial axis, are evidence of the drilling process and are more difficult to assess. The drilling process removes rock and causes the in-situ stresses to redistribute, or concentrate, around the borehole in a well-known elastic manner.¹⁹ In addition, drilling not only breaks the rock that is removed to form the borehole, but also may mechanically damage a volume of rock surrounding the hole.²⁰ This type of damage is called plastic deformation, in contrast to elastic, or reversible, deformation. In addition to plastic deformation, drilling fluid may react with clays, causing swelling and altering near-wellbore velocities. Mud that invades pore space displaces formation fluids that probably have different properties, also altering sonic velocities. Drilling-induced variations may be more gradual than variations across layer interfaces.



▲ Compressional and shear radial profiles in an anisotropic inhomogeneous formation. The profile of variation in compressional slowness (Track 4) is created by tomographic reconstruction based on tracing rays through a modeled formation with properties that vary gradually away from the borehole. The percentage difference between observed slowness and slowness of the unaltered formation is plotted on color and distance scales to indicate the extent of difference away from the borehole. In these sandstones, identifiable from the gamma ray log in Track 2, compressional slowness near the borehole varies by up to 15% from far-field slowness, and the variation extends to more than 12 in. [30 cm] from the borehole center. The borehole is shown as a gray zone. Shear radial profiles show the difference between fast shear-wave slowness and far-field slowness (Track 1) and the difference between slow shear-wave slowness and far-field slowness (Track 3). Large differences in shear slowness extend out to almost 10 in. [25 cm] from the borehole center. The radial variation in compressional and shear velocities is drilling-induced.

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▲ Sonic-imaging data-acquisition geometry. Designed to detect layer boundaries and other inhomogeneities roughly parallel to the borehole, the sonic-imaging technique records reflected signals (red rays) from interfaces tens of feet away. Borehole signals (black rays) must be filtered out.

Alteration in near-wellbore properties can cause velocities to increase or decrease relative to the unaltered, or far-field, formation. Usually, drilling-induced damage reduces formation stiffness, causing velocities to decrease near the borehole. However, when drilling fluid replaces gas as the pore-filling fluid, the resulting formation is stiffer, so compressional velocity increases near the borehole.

Radial alteration of rocks and fluids affects compressional and shear velocities differently. Alteration that reduces stiffness of the rock fabric, such as drilling-induced cracking or weakening, causes both P and S velocities to decrease. However, a change in pore fluid has little effect on S velocity, while P velocity may change dramatically. For example, when drilling fluid replaces gas, P -wave velocity increases, but S -wave velocity is relatively unaffected. Complete characterization of radial inhomogeneity requires analysis of radial variation of compressional and shear slownesses.

A radial compressional-slowness profile is generated by collecting P -wave data for multiple depths of investigation, from near the wellbore to the unaltered, far-field formation. This requires recordings from a wide range of transmitter-

receiver spacings. Ray-tracing techniques invert the refracted compressional arrivals to yield compressional slowness versus distance from the borehole.²¹ The difference between near-wellbore compressional slowness and far-field compressional slowness can be plotted along with depth of radial alteration (previous page). In this example, radial variations of shear slownesses are also plotted.

Radial variations in shear slowness are quantified through inversions of the broadband dispersions of flexural and Stoneley modes.²² At high frequencies, these dispersive modes investigate the near-wellbore region, and at low frequencies, they probe the unaltered formation far from the borehole. Dispersion data from a wide range of frequencies help produce the most reliable radial profiles of variations in shear slowness.

Some of the most challenging inhomogeneities to characterize are those that do not intersect the borehole. These may be vertical fractures or faults near a vertical borehole or sedimentary interfaces near a horizontal well. Detecting such inhomogeneities requires a method that looks deep into the formation and that is able to detect abrupt changes in formation properties.

The sonic-imaging technique, sometimes called the borehole acoustic reflection survey, provides a high-resolution directional image of reflectors up to tens of feet from the borehole (left).²³ Consequently, this technique has significant potential application in horizontal wells. To create an image, the tool records waveforms of relatively long duration from the monopole transmitters. Receivers must be distributed around the tool to allow the azimuths of the reflections to be distinguished.

Complex data processing similar to that designed for surface seismic surveys is applied in a multistep process. First, a compressional-velocity model of the region in the vicinity of the borehole is created using the P head waves. Then, to extract reflected energy, the traditional sonic arrivals, including P and S head waves and Stoneley waves, must be filtered from the waveforms for each shot. The filtered traces are input to depth migration, a process that positions reflections in their correct spatial location using the velocity model.

The migration process formally converts a set of amplitude and traveltme measurements into a spatial image of the formation. This can be viewed as a triangulation process in which the distance and the dip of a reflector relative to the borehole are determined by the signals recorded at receivers at different TR spacing. The receivers at different azimuths around the borehole measure different distances to a reflector depending on the azimuth and the dip of the reflector relative to the borehole.

The sonic-imaging technique was developed in the 1980s, but results have improved with advances in sonic tools and processing methods.²⁴ The technique has been used to image steeply dipping beds from near-vertical boreholes and sedimentary boundaries from horizontal wells. For examples of sonic imaging and other applications of sonic measurements see "Sonic Investigations In and Around the Borehole," page 14.

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