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.

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.

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. This first head wave in the mud is known as the compressional head wave, and its
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 \( \Delta t \), or slowness, and is the reciprocal of speed. This is the most basic sonic-logging measurement.

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 and body 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. 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

- \( \theta_1 \) is the angle of incident and reflected \( P \)-waves. \( \theta_2 \) is the angle of refracted \( P \)-waves. \( \theta_s \) 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 \( 90^\circ \), a head wave is created.

\[ \sin \theta_1 = \frac{\sin \theta_2}{V_p} \]

<table>
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\^ Wavefront reflection and refraction at interfaces, and Snell’s law. \( \theta_1 \) is the angle of incident and reflected \( P \)-waves. \( \theta_2 \) is the angle of refracted \( P \)-waves. \( \theta_s \) 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 \( 90^\circ \), a head wave is created.
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. 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. 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. 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.

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-
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.\(^6\) 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.\(^7\)

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.


\(^5\) 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.


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. 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 on the STC projection log (right), 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
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.\(^1\)

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.\(^2\)

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.\(^3\)

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.\(^4\) 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 (TIV).

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.


\(^{14}\) This holds for alignments on scales that are smaller than the wavelength of the waves in question.
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 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). This example shows recording of flexural waves at 13 receiver stations with eight receivers distributed in a ring at each station.\(^{15}\)

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

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15. Offline is sometimes referred to as crossline.
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. Then, the waveforms corresponding to fast- and slow-shear orientations undergo semblance processing to obtain the fast and slow shear-wave slownesses. 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 and 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. 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. 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.

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. 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. 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). 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 traveltime 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. 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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