CHOOSING THE RIGHT SONIC SERVICE

Jennifer Market, Senergy

ABSTRACT

Borehole sonic data are acquired for a myriad of uses, including pore pressure prediction, porosity, seismic correlation, wellbore stability, hole size determination, fracture characterisation, permeability, cement bond analysis and more. One of the difficulties in the well planning stage is determining the best sonic tool/service for the purpose, as we must balance such factors as cost, data quality, environmental challenges, conveyance risk and timeliness of data delivery to select the right service for the application.

This paper will review a variety of applications and environments, such as the acquisition of compressional data in large shallow wells for accurate pore pressure prediction, obtaining good quality shear data in slow and fast formations, and logging azimuthal shear velocities for production enhancement in unconventional wells. Recommendations will be suggested for optimal and cost-effective sonic logging programmes. LWD and wireline options will be considered as well as a variety of types of hardware. As this is a non-partisan presentation, no trade names or specific services will be referenced. Particular configurations, such as optimal source-receiver spacing, azimuthal capabilities, or transmitter frequency ranges will also be suggested, but again in a generic sense.

While it is natural to focus attention on hardware configuration and signal quality, it is equally important to consider service delivery factors such as reliability of hardware, telemetry speed, waveform processing quality and data delivery. We will consider a variety of scenarios and applications, considering how to weigh these service quality and delivery factors in each instance. For example, if the primary application of sonic data for a well is real-time pore pressure prediction, then telemetry rates, automated processing quality, and data monitoring are critical, but whether the hardware is capable of acquiring high resolution azimuthal data or very slow shear may not be as essential. On the other hand, if the primary application is fracture characterisation in a reservoir, perhaps the azimuthal shear data quality is paramount while the turn-around time for processing the data may be less important. We will recommend standard deliverables for each application.

INTRODUCTION

Acoustic data are used in a wide variety of applications, including classic applications such as sonic porosity, pore pressure prediction, cement bond characterization and seismic correlation as well as in more novel applications such as geosteering, 3D anisotropy, fracture characterization, and brittleness mapping in unconventional reservoirs. There are also a wide range of tools and services available in today's market, spanning from "cheap and cheerful" short-spaced monopole tools to advanced multi-array, long-spaced azimuthal tools. Most of the tools can be configured in a number of different manners to optimize data collection for particular applications. While economics should be considered when selecting the best service, it shouldn't be the only factor driving the decision of which tool (and service) to use.

In this paper, we begin with a review of types of acoustic tools and services commercially available, focusing not just on hardware but on processing and interpretation. Next is a consideration of various environmental effects on sonic data, such as hole condition, casing, and wellbore inclination. This is then followed by a review of selected applications which use sonic data, paying particular attention to which type of sonic data is needed for each application. Combining all those factors, we consider some scenarios whereby we must balance application, tool availability, environment, and economics.

REVIEW OF ACOUSTIC TOOLS

As there is a variety of acoustics tool "flavours" available, we will begin with a short review of various types of acoustic tools available in the industry, as well as their capabilities, limitations, and operational considerations. [1]

Wireline Source configurations come in two main varieties: monopole and cross-dipole.

- **Monopole:** The earliest sonic tools were monopole tools, designed to measure compressional velocities for seismic correlation. Today, both legacy (20th century) and modern (21st century) tools are still widely in use, largely because they are inexpensive and shorter than cross-dipole tools (and thus more easily combined with multiple other tools and less likely to be damaged in tortuous wellbores). Normally, the main purpose for running these tools is for compressional (DTC) and refracted shear (DTRS) as well as cement bond estimates. However, most models can also be configured to record the signal for a longer period and also measure Stoneley waves. These tools are not suitable for shear anisotropy measurements. The quality of the data from wireline monopole tools varies widely, largely based upon the vintage. Environments which can challenge monopole tools are: very fast DTC, very slow DTC, excessive alteration/invasion, large holes, and poor hole condition. If any of these conditions are expected, it is best to choose a premium modern tool.
- **Cross-Dipole:** Cross-dipole sources were introduced in the 1990's. These tools include broad-frequency dipole sources designed to measure azimuthal shear in both fast and slow formations. (Harrison et al. 1990). Compared to traditional monopole tools, these tools have broader frequency sources and longer source-receiver spacing, which allows for measurements in a wider range of environments and enables investigation of the near- and far- wellbore. Cross-dipole configurations can acquire DTC and DTRS, but if the source is configured in a standard low-frequency mode, the response is not suitable for DTC and DTRS in fast formations. Cross-dipole modes are primarily suited for acquiring DTS (in fast and slow formations) and shear anisotropy. Environmental challenges for cross-dipole logging include: very slow shear, centralisation, and poor hole condition. In adverse environments, there are marked differences in tool capabilities by model.

Industry cross-dipole tools combine both monopole and cross-dipole sources into the same tool design to be able to provide DTC, DTRS, slow shear, shear anisotropy, and cement bond applications in one tool.

LWD tools were introduced in the mid 90's, (Minear et al. 1995) to provide velocities for real-time applications and in environments where wireline logging is expensive or impractical. The industry has been relatively quick to accept the compressional and refracted shear measurements, but slower to embrace the slow shear measurements due to the complexities surrounding dispersion corrections in the LWD environment. The rotation of the LWD tool string means that if an azimuthal sensor in installed on the tool, then azimuthal slowness images can be created, for use in geosteering, shear anisotropy, etc. This is an emerging area, with tool capabilities varying considerably by vendor. (Market et al. 2011 and Mickael et al. 2012). There can be minimum ROP requirements to enable good azimuthal tracking, which should be considered in the planning stage.

- **Unipole:** "Unipole" is the term used to refer to tools with a single transmitter placed on one side of the collar (Wang, et al. 2011) which generates an azimuthally focussed pseudo-monopole wave suitable for creating compressional, refracted shear, and Stoneley waves. The data can also be suitable for cement bond investigations. The main variation in the designs is the source frequency and strength. If Stoneley waves are required, it is best to choose a tool with a broad or low frequency source. In very fast formations, large hole, and poor hole condition, modern tools (with higher source strengths) are recommended. Some tools have azimuthal capabilities. Unipole configurations are suitable for creating compressional and shear images. (Mickael et al. 2012).
- **Monopole** LWD tools are also available, either as discrete sources placed around the collar (fired in concert) or as segmented ("ring around the collar") designs. Monopole sources generate signals suitable for DTC, DTRS, and Stoneley waves. The data can also be suitable for cement bond investigations. Some monopole tools have azimuthal capabilities for creating compressional and shear images (it should be noted that monopole sources are less directionally sensitive than unipole sources).

[1] "Sonic" and "acoustic" are used interchangeably.

Slowness is the inverse of velocity and the two terms are used freely throughout the paper.

- **Dipole** LWD sources were introduced in the late 90's. (Varsamis et al. 1999). The primary purposes for the dipole tools were to measure extend the range of earlier tools to cover DTC and DTS in slow formations. The dipole-derived "slow shear" measurements are not quite the same as in the wireline environment, and the relatively large uncertainty in the slow shear measurement led to the development of quadrupole and combination multipole tools. However, dipole tools are still widely available in the industry and can be used to determine shear velocities in slow formations (if the dispersion effects are well characterised). Azimuthal versions of dipole tools are available and can be used for shear anisotropy measurements. (Market et al. 2011). Dipole modes are suited for DTC, DTS (in fast and slow formations) and shear anisotropy (if the tool is also equipped with an azimuthal sensor). They can also be used in cement bond analysis.
- **Quadrupole** LWD tools were introduced to mitigate the "slow shear" uncertainties in LWD dipole data. (Dubinsky et al. 2003). While quadrupole waves are not as directionally focused as dipole waves, they can be well suited to deliver shear in slow formations and some information about shear anisotropy. Quadrupole modes can acquire DTC and DTS (in fast and slow formations). They can also be used in cement bond analysis.

Modern sonic tools are highly configurable. Most can programme the source characteristic, select which modes to acquire (e.g. monopole, crossed-dipole, quadrupole), which type of isolation to use, and more. In the well planning stage, it is important that the service company and operator discuss the purpose of the sonic data acquisition and the target application in order to ensure the optimal configuration.

Tool Size: When selecting an LWD tool for a logging programme, it is important to remember that not all varieties come in all sizes. Some service providers have premium tools in some sizes and more vintage tools in other sizes. In the planning stage, it is worthwhile to discuss the suitability of the available tools. For example, if the logging environment requires the latest model tool, but only older models are available in that size, it may be worth considering using different tool vendors in different hole sections. Don't forget to consider contingency plans. For example, if the primary application is geosteering, and the bit size is planned to be 8 ½" with a contingency for a 6" hole, it isn't sufficient to have a 6 ¾" azimuthal tool and a 4 ¾" non-azimuthal tool on hand.

In wireline logging, tool size is not specifically matched to hole size in wellbores 6" and larger, but in holes smaller than 6", size does become a consideration. Generally, standard tool diameters range from approximately 2 7/8" to 3 5/8" (any stabilizers or centralisers would increase this base diameter). However, some varieties of tools do come in 2 ¼" diameters. As with LWD, different types of tools are more readily available in some sizes than others. In the planning stage, it is essential to consider which models of tools are available for the expected hole/casing sizes.

HPHT (High Pressure and High Temperature): Standard temperature ratings of 150C and 20 kPSI are common throughout the industry, but many vendors have offerings in excess of that. LWD tool ratings vary by vendor, with several offering of sonic tools in the 180C and 30 kPSI range. Not all sizes are available at these ratings. Particularly, smaller tools often have lower pressure ratings due to design constraints. Wireline tools also vary by vendor, but sonic tools are widely available up to 260F and 35 kPSI.

LWD OR WIRELINE?

Once we've made the decision to acquire sonic data, we must decide whether to acquire it on wireline, LWD, or both. The first criterion to consider is the application. For real-time applications where the data are needed very close to drilling time, such as pore pressure prediction, seismic correlation, geosteering, or mud selection, LWD is the obvious option. For advanced applications, such as 3D anisotropy, deep fracture characterisation, shear velocities in very slow formations, holes smaller than 6", or temperatures >175C, wireline tools are the better option. For most applications and environments, however, solutions are available both on LWD & wireline and it is economy and logistics which help decide the best choice. We should consider running LWD as "insurance" in cases where wireline is planned but there are risks due to hole stability, conveyance (wellbore trajectory) alteration or other conditions.

To get the total cost for acquiring sonic data, we have to include not only the cost of the service, but also the cost associated with rig time and conveyance risk. In shallow land wells, these costs might be quite low, while in deepwater, extended reach wells, rig time cost will likely be a critical factor. In general, in shallow to moderate depth vertical wells onshore, it is usually more economical to run wireline tools while in deepwater or extended reach environments, it is often more economical to use LWD services. **Table 2** lists some of the complementary strengths and weaknesses of wireline and LWD data.

	DTC	DTS, Fast Forrmations	DTS, Slow Formations	Stoneley	Classic Anisotropy	Azimuthal Images
Wireline Monopole	*Use 21st century tools in extreme environments*	*Use 21st century tools in adverse environments*	*Some Possibility of getting DTS from Stoneley.*	*Tool should be configured to record longer*		
Wireline Cross-Dipole (tools include Monopole)			*Upper limit ovaries by tool model and environment.*			*Some possibilities with certain tool models*
LWD Unipole	*Use 21st century tools in adverse environments*		*Some Possibility of getting DTS from Stoneley*	*Use models with low freq. Source, configured to listen longer*		*If tool is configured with azimuth sensor*
LWD Mono. +Dipo.	*Quality in very fast formations varies by model*		*Uncertainty & Upper limit varies by tool model and environment.*		*If tool is configured with azimuth sensor*	*If tool is configured with azimuth sensor*
LWD Mono.+Quad.	*Quality in very fast formations varies by model*		*Uncertainty & Upper limit varies by tool model and environment.*			*If tool is configured with azimuth sensor*
LWD Mono + Dipo. +Quad	*Quality in very fast formations varies by model*		*Uncertainty & Upper limit varies by tool model and environment.*		*If tool is configured with azimuth sensor*	*If tool is configured with azimuth sensor*

Table 1. Summary of suitability of each type of tool for data acquisition.

Wireline Pros	LWD Cons	LWD Pros	Wireline Cons
Premium tools operate in wide range of formation velocities	LWD tools don't cover as wide a range of formations as WL	Real-time data available for decisions while drilling	Tools can only be run after the section is drilled
Long-established anisotropy techniques	Industry is still establishing anisotropy methods	Short formation exposure time (minimal alteration)	Longer formation exposure time – possible alteration, invasion, and borehole damage
Quiet environment – high signal-to noise	Drilling environment can be noisy	No extra rig time needed to acquire data	Extra rig time required to acquire data
Low uncertainty in deriving "slow shear" from flexural waves	Higher uncertainties in "slow shear" calculations	Minimal conveyance risk	Conveyance risk , especially in high angle hole or tortuous well paths
Tools available up to ~260 C	Tools limited to ~180C	Large collar means tool less eccentred even in large holes	Small tool can make centralisation difficult in large holes
Very slim (2 ¼") tools available	Smallest Tool size is ~4 ¾"	Strong collar	Tool can sag and pipe-conveyed logging can pose integrity risks
Advanced applications – Deep fracture imaging, 3D anisotropy, low % anisotropy	Advanced applications still in development	Logs acquired in open holes.	Wellbore stability may require immediate casing, meaning logs are acquired through casing

Table 2. Complementary strengths and weaknesses of wireline and LWD sonic tools and environments.

TOOL RELIABILITY AND QUALITY CONTROL

In the process of selecting a tool, we need to consider the reliability of the hardware and how the raw tool data are quality controlled. For the most part, sonic tools are relatively reliable in terms of starting up and acquiring data (though of course there are some variations by specific tool model). However, the three main components of a sonic tool – the transmitters, receivers, and isolation system – can degrade over time and a "health check" should be performed both regularly in the shop and also on the rig before each run. Ideally, the results of these tool checks should be included in a short report that is archived with each run of data. While we ideally would only use tools which are operating at 100% of specifications, sometimes it is necessary to use tools whose transmitters or receivers aren't perfectly matched, whose isolation is worn, or which maybe even has a "dead" receiver. Modern sonic tools are built with a significant amount of data redundancies in place, such that it is often possible to derive a usable log from a slightly ailing tool. However, high-end applications such as anisotropy, deep fracture imaging, and velocities in extreme formations require the tools to be functioning at or near full spec. **Figure 1** shows an example of a receiver "health check". The plot on the left shows a tool working within specification (receivers are closely matched), while the plot on the left shows a tool whose receivers are quite poorly matched. The tool on the right should be able to get reasonable compressional and shear logs (albeit some special processing methods might be needed). However, if we wanted to use the tool on the right to characterize very low amounts anisotropy, we might run into difficulties.

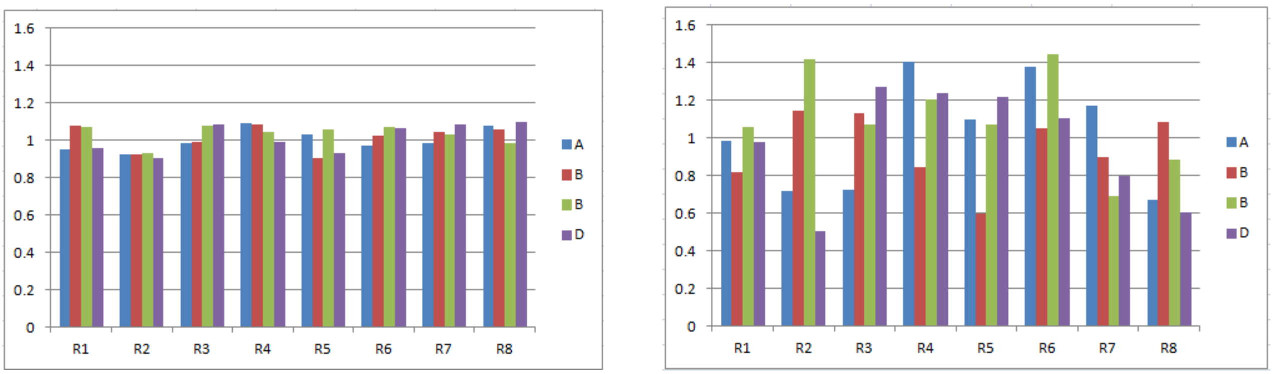

Figure 1. Example of a receiver "health check". The example on the left shows a tool working within specification (receivers are closely matched), while the plot on the left shows a tool whose receivers are quite poorly matched. (After Market et al. 2009).

DATA PROCESSING AND INTERPRETATION

The quality, consistency, and timeliness of the data processing and interpretation are essential considerations. The data analysis might be done by the end user in an oil company, by the tool provider, or by a third party (consulting) company. In fact, with many applications, the data might be analysed by all three at different stages. Data collection and interpretation usually passes through the following stages:

- **Pre-well planning** should involve the end user of the data and a technical person from the service provider(s) who understands the capabilities and limitations of the services offered. This is the stage at which the target application of the sonic data and the expected environment (formation types, hole conditions, etc.) are discussed and the appropriate tool, configuration and service selected. Expectations for the data delivery and timing should be made clear.
- **The field engineer** is then responsible for setting up the tool (as per the agreed-upon configurations), performing rig site tool health checks and running the tool in hole.
- **Automated downhole processing** is performed by the tool, which in most cases is standard semblance processing and automatic labelling of DTC, DTS, etc. The level of accuracy of the automated picking is very much a dependent upon the formation, environmental condition, tool settings, and the particular model of tool. The most common issues are mis-labelling of peaks, where the shear arrival is labelled as the compressional (common in fast formations), the casing arrival might be labelled as compressional, etc.
- **Real-time data monitoring** The field engineer (or offsite monitoring centre) is responsible for quality control of the raw data as well as monitoring the real-time data and correcting the velocity picks as necessary to give a

usable log. How closely the real-time data need to monitored depends upon the application – in some cases, the end user won't really be looking at the data until weeks later, so the primary purpose of the QC is to make sure that the raw data quality is good. For other applications, such as real-time pore pressure prediction, the velocity data may be absolutely critical real-time to make drilling decisions and the data should be monitored and corrected. (Blyth et al. 2012). When choosing a service provider, the reputation for real-time data quality should be a primary consideration if the application is critical real-time.

- **Rigsite processing** of the data usually follows. In the case of wireline, the raw waveform data are transmitted up the wire, while with LWD the full waveform data are available once the tools have been brought to surface and read. The field engineer has software onsite to enable reprocessing of the raw waveform data (such as changing the frequency filters, etc.) and repicking the velocity curves. We should keep in mind that the field engineers are usually trained to be comfortable picking basic DTC and DTS modes, but that advanced processing such as anisotropy, or special signal processing to handle extreme environments is usually done in town.
- The data are now available to be sent into a **processing centre** for further analysis. The processing centre may be at the client, service company, or a third-part consultant. The processing centre is usually a combination of experienced log analysts, petrophysicists, geophysicists, rock mechanics/formation damage experts, and other specialists. Depending upon the application, the processing centre is responsible for ensuring good quality velocity curves and common "answer products" such as porosity, permeability, top of cement, etc.
- **Advanced Interpretation**, such as 3D anisotropy, deep fracture imaging, and advanced signal processing for noisy datasets may need to go to an advanced processing centre. Whether it is the client, the service provider, or a consulting company, there are usually a small number of advanced sonic specialists who handle the advanced interpretation, so the data are likely to be passed to a global focal point.

When considering data processing/interpretation options, keep in mind that the tool and the interpretation can come from different providers.

DELIVERABLES

At present, there is little standardization in the industry in terms of sonic deliverables. As part of the planning stages, the end user (operator) and service provider should agree in advance which data will be delivered as well as the preferred format, curve names, and timetables. Standard deliverables for sonic vary by application but in general should include:

1. DLIS file containing the raw waveform data for all modes. When applicable, the individual components of the summed waveforms should be included (i.e. the data from each receiver array). The acquisition parameters such as waveform digitization rates, digital delays for each receiver, downhole filters, normalizations, and tool configuration parameters should also be included. These parameters would ideally be stored in the DLIS file's parameters section or, if that isn't possible, in the text header. Calliper, gamma ray, and tool orientation data should be included as well. This file should contain all the data needed to reprocess the data. This file should be as complete as possible, as we never know what new applications may be developed in the future which might allows us to dig hidden treasures out of old data.
2. DLIS file containing the processed curve and array data – i.e. slownesses, quality control curves, interpreted curves such as permeability, porosity, etc. as appropriate for the application. This DLIS file should contain any processing parameters used. These parameters would ideally be stored in the DLIS file's parameters section or, if that isn't possible, in the text header.
3. LAS file which is a slimmed-down version of the processed DLIS file to contain the primary deliverable for the target application. This is the main file that will likely be loaded to an operator's archives and used by a variety of disciplines and should be clear and succinct.
4. Digital plots showing the processed data, including both curves and accompanying QC plots. The log headers should contain the processing parameters used and the tracks clearly labelled.
5. Short report showing the tool "health check" and summarizing the acquisition and processing parameters.
6. In the case of any interpreted "answer products", a detailed report of reviewing the methods use and discussion of the results should be included.

Clarity is essential. There may be multiple versions of the "answers" at various stages. The deliverables should clearly indicate that they are "real-time", "quick look", "final", etc. It is quite common that an end user has to wade through a confusing pile of files to try to determine which version of the data to use. This is time consuming and costly. The end users aren't always specialists who see hundreds of sonic logs a year and are familiar with all the intricacies of sonic data. They will be grateful for simplicity and clarity.

Timeliness of Data Delivery When planning the well, it is essential to discuss the expectations of data delivery. These will vary greatly by application. The service provider and end user should agree on a timetable of delivery.

ENVIRONMENTAL CONSIDERATIONS

Formation Velocity (Slowness) and Hole Size: One of the most essential parameters – the slowness operational ranges of each model – is one of the most difficult values to pin down. It is also one of the most essential considerations when choosing a tool. For each combination of formation properties, hole size, and mud characteristics, there are natural resonant frequencies. In simple terms, if the tool is well tuned to the formation's natural response, the signal quality is better.

Since there are a wide range of sources available in the industry which vary in frequency content, amplitude, and signal shape, it is not possible to report the exact range of operation for each particular tool (and each configuration) here. However, **Figure 2** gives a generalised overview of the relative ease/difficulty of logging in a wide range of formation slownesses and hole sizes. As an overview:

- **Compressional logging in very fast formations** can be difficult, as the majority of the energy is converted to shear waves, which can lead to low signal-to-noise for DTC in fast formation and holes in the logs. This effect can be alleviated by a strong unipole or monopole high frequency source.
- **Compressional data in very slow formations and/or very large holes** can be difficult to process accurately, as leaky-p waves (also somewhat inaccurately called "fluid arrivals") can make it difficult to determine the true compressional velocity. Special processing techniques may be needed when the compressional slowness is within 15% of the mud slowness. (Market et al. 2002).
- **"Refracted shear"** is the term used to describe shear velocities measured directly (no geometrical dispersion corrections needed) in formations where the shear velocity is faster than the mud velocity. While often referred to as "monopole shear" it is also possible to acquire refracted shear with dipole and quadrupole modes. Refracted shear is generally good in very fast formations, though the amplitude drops as the velocity approached the mud velocity and thus becomes more difficult to detect.
- **"Slow shear"** is the term often used to describe shear velocities slower than the mud velocity (not to be confused with "fast" and "slow" shear in terms of anisotropy). Slow shear is derived by measuring interface modes (Stoneley, flexural, quadrupole) and correcting for any geometric dispersion effects. The resonant frequency of these modes decreases markedly as the hole size increases. In addition, the amplitude of the modes decreases as the formation becomes slower. Designing acoustic transmitters that are both very strong and very low amplitude can be challenging. These three effects together combine to mean that, as the hole size increases, the upper limit for shear measurements decreases.
- **Large hole sizes** generally yield lower signal quality than small holes, due to attenuation effects. The acoustic wave travels from the transmitter, through the mud column, along the wellbore, then back through the mud column to be detected by the receivers. Any time spent travelling through the mud column attenuates the signal. Larger holes mean a larger mud column, which in turn leads to lower signal-to-noise ratios. It is important to remember that with LWD tools, it is the annulus size, rather than the actual hole size, we should use when considering attenuation effects. When configuring an LWD tool string which includes a reamer (hole opener), placing the sonic tool below the reamer (where the hole is smaller) is generally preferred.
- **LWD shear in small holes** can be prone to larger uncertainties than in large hole, so we need to take care in applying dispersion corrections.

Figure 2. shows a very generalised view of the ease of acquiring compressional and shear adata as a function of formation slowness and hole diameter. There are many assumptions in these models and the response won't exactly match every tool in the industry, but the trends should be useful. For example, if the formation/hole size we are

planning to log is in the green area, we expect that the data quality will be good and even older generation tools may well be suitable. On the other hand, if the expected environment is firmly in the red zones, then we need to be much more careful in selecting and configuring the tool for the best chance at acquiring good quality data. These charts are only very generalised guidelines (even generalising over both LWD and wireline). End users and tool providers should always discuss the upcoming data acquisition programme and the expected environment to determine which type of tool is needed and if it is possible to acquire the required data. It is much better to know up front that it is unlikely to get the expected data than to find out after the job!

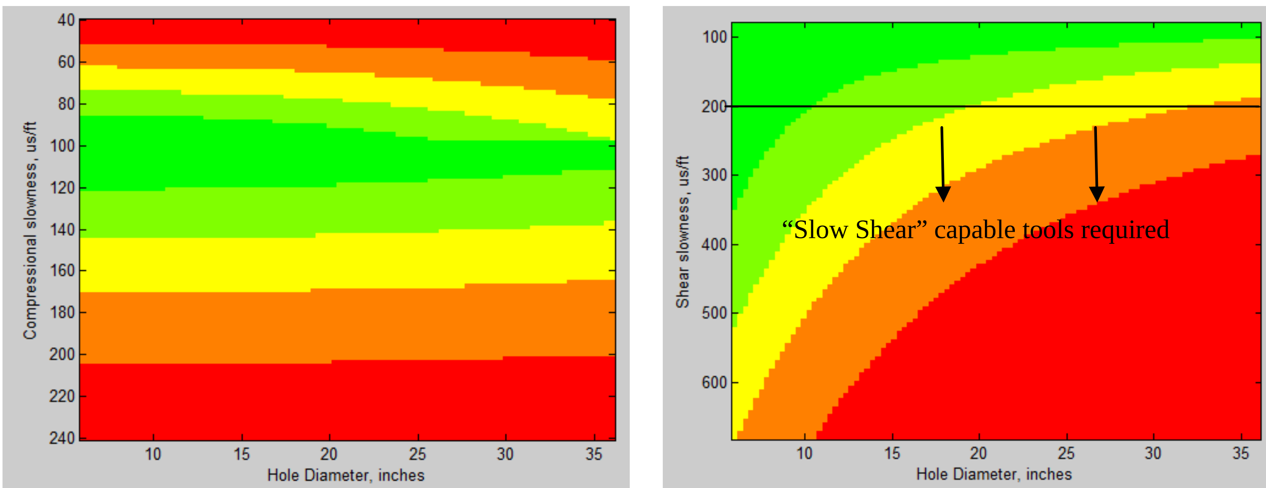

Figure 2. A very generalised view of the ease of acquiring compressional (left) and shear(right) data as a function of formation slowness and hole diameter. There are many assumptions in these models and the response won't exactly match every tool in the industry, but the trends should be useful. (The mud slowness in this model was 220 us/ft).

Centralisation As a general rule, we should centralise acoustic tools whenever possible to enhance the data quality. The primary reasons for wanting to centralise sonic tools are 1) to combine data from multiple azimuthal receiver arrays to enhanced the desired signal and suppress unwanted arrivals and 2) to provide symmetry such that we can distinguish true formation effects such as anisotropy, fractures, permeability, and hole size variations from tool position effects. (Market et al. 2009). Tool centralisation isn't always essential (or even possible), but we should consider how tool position will affect the target application to decide whether extra measures should be taken to ensure centralisation. A calliper tool should be run in the string (if one isn't actually part if the sonic tool) with the acoustic tool in order to know both the hole size and the tool position.

DTC and DTRS are the least affected by tool position, while more complex modes such as flexural and quadrupole waves will suffer more from eccentring. In very large holes, we might even intentionally eccentre the sonic tool in order to have at least one receiver array close to the borehole wall to get a good signal. However, in this case, we would not expect to acquire usable flexural data. If we know (or suspect) that the tool is not well centralised, we should process the individual array data as opposed to only the azimuthally combined waveforms. If the tool is not well centred, we can expect to have more uncertainty in slow shear dispersion corrections. This doesn't mean that it is impossible to acquire slow shear when the tool is mild-moderately eccentred, it just means that we should use caustion and ensure that an experienced acoustic data analyst reviews the data. Due to operational practicalities, it is common that LWD aren't fully centralised, but if care is taken in assembling the LWD tool string, it is often possible to place the tool in a position that it is likely to remain fairly centralised (e.g. between stabilisers, or away from and devices which forcibly off-centre other tools). Keep in mind, also, that in normal hole size, there isn't so much room for an LWD sonic tool to be eccentred, especially as standard designs of LWD sonic collars include wear bands/offsets to prevent the source/receivers from contacting the wall.

Hole Condition Thus far, in our discussion of hole size, we've assumed that the hole is in good condition – nicely circular and with smooth sides. Since this is rarely the case, we need to consider the effects of poor hole condition on sonic data. **Rugosity** (irregular surface of the wellbore) can affect sonic data quality. Interface modes (e.g. Stoneley, flexural, and quadrupole waves) are more affected than refracted modes. Often, even in very rugose wellbore, we can still measure DTC and DTRS, while the interface modes are very poor quality. If the hole is **elliptical**, it has the effect of eccentring the tool, and in the case of wireline, it is quite likely that the tool will settle into the groove in an elliptical wellbore. While this has relatively little effect on the compressional and refracted shear modes, eccentricity can seriously affect the quality of the flexural mode and possibly even make the data unusable for anisotropy determination. (See Centralisation discussion, above). Unfortunately, elliptical wellbores are where anisotropy measurements cab be of interest, as there is a reason that the hole is elliptical in the first place – the stresses around the wellbore aren't equal. **Break-out** (or irregular shape) has similar effects as rugosity and ellipticity combined. DTC and DTRS are relatively tolerant of break-out until it becomes severe, while interface modes are affected much more by minor break-out.

In cases of poor hole condition, it can be worth processing the individual receiver arrays separately (rather than summing or differencing the signals) to enhance the results.

Mud properties can affect the quality of the sonic data to varying degrees. **Mud Weight and Viscosity**: The heavier (and more viscous the mud), the more it will attenuate the acoustic signal. While the effects aren't as extreme as with ultrasonic tools (such as cement bond logging tools or ultrasonic "callipers"), attenuative mud can still can be a factor. Higher frequency modes, such as compressional in very fast formations are more likely to be noticeably affected than lower frequency signals. **Mud Speed**: The velocity of sound in the mud determines the range of shear velocities which may be directly measured vs. derived from interface modes (e.g. Stoneley, flexural, quadrupole). Slower mud speeds extend the range of the refracted shear measurements (which is generally a good thing.) Mud speed is a parameter that is seldom well known, especially while drilling. It changes significantly with type of base, composition of the solids, pressure and temperature. This leads to some uncertainty in slow shear measurements, but can be at least partially mitigated by choosing a tool which has ultrasonic transducers (either in the sonic tool or on another sensor), which can help to estimate the mud speed. (Market et al. 2011). **Flow Rates:** High mud flow rates can be a significant source of noise and adversely affect signal quality (LWD). One method used to combat these effects is to use the data acquired during connections (pumps off) to not only QC the data, but also to optimize the tool configuration. (Blyth et al. 2012). **Gas in the mud column:** Even small amounts of gas released into the wellbore will significantly attenuate the signal. High frequencies are the most susceptible, so often the compressional is more affected than the low frequency interface modes.**Air drilling**: Acoustic tools are not designed to operate without fluid in the borehole.

Alteration/Invasion and Depth of Investigation Similar to resistivity tools, the depth of investigation of sonic tools is largely determined by spacing between the transmitter and the frequency of the source (combined with the resonance frequency of the formation) as a rough estimate, it is one wavelength. For example, a 100 us/ft wave at 10 kHz has a wavelength of 1 ft. The same 100 us/ft wave at 5 kHz has a wavelength of 2 ft. (Market et al. 2009). Thus, tools with broad frequency sources or multiple sources at different frequency can measure both near the wellbore and deep into the formation. This can be quite useful when investigating alteration, wellbore damage, and invasion. Modern tools routinely use this aspect to measure the anisotropy both in the near- and far- wellbore to distinguish drilling-induced stress from intrinsic stress. (Sinha et al. 2000).

"Drilling Noise" and Tool Placement: "Drilling Noise", which is primarily the noise caused by fluid circulating in the wellbore (Minear et al. 1995) can vary greatly, depending on flow rates, hole size, and mud properties. High flow rates, heavy mud, and small annuli can lead to consider turbulent noise. While modern LWD tools are designed to suppress the effects of this noise (Market et al. 2007) it can still significantly affect the signal-to-noise ratio and thus, especially in extreme environments, make it difficult to acquire a good log. One way to partially mitigate the problem is to process the "pumps off" data collected during connections and on the trip out, and use it as a guide to aid in the processing of the noisy data. Since the reduction of this noise is largely done through mechanical means, the effectiveness of the suppression varies considerable by tool model. Some models which are particularly prone to this noise will benefit from being placed as far as possible from the bit (or the reamer).

Cased Hole Sonic log quality through casing is heavily dependent upon the cement bond quality. In cases of poor bond, it can be difficult or impossible to acquire a log through casing, but when there is a reasonable bond, both wireline and LWD tools can acquire compressional and refracted shear logs through casing (assuming the same hole condition and velocity considerations as in open holes). If the formation slowness is close to or faster than the casing slowness, special signal processing might be needed to distinguish DTC from casing. Obtaining "slow shear" through casing via Stoneley, flexural, or quadrupole methods is often possible, but care must be taken in the dispersion corrections to account for the casing and cement layers. Low frequency waves "see through" casing/cement/fluid layers better than high frequency signals, so sometimes if the cement bond is a bit poor, low frequency sources are better for detecting the formation compressional and refracted shear than more traditional monopole modes. The amplitude of the waves reflected from the casing can be also used as an indicator of cement bond quality, which will be discussed further in the "Applications" section. If azimuthal applications are required through casing (such as anisotropy or azimuthal cement bond) a non-magnetic navigation package should be used (this may sound obvious it is often overlooked!).

High Angle wells pose several challenges to acquiring good quality acoustic data. As with any wireline data acquisition in high angle holes, there are **conveyance risks**. We should consider if LWD is viable for the application. It is common practice to run LWD data as "insurance" even if a wireline run is planned, in case there is trouble getting the wireline tool string down. **Centralisation** can be difficult, as making tool centralisers strong enough to keep the tool in the centre of the hole but yet flexible enough not to be stuck is a challenge. Also, if the hole is elliptical (which is quite common for horizontal wellbores), the tool naturally sits in the grove. Thus, we face the challenges of off-centred tools. While cross-dipole tools are designed to measure **shear anisotropy**, the flexural mode is sensitive to the shear perpendicular to the axis of the tool. However, in a high angle hole, we are more likely to be interested in the difference between the shear in the x- and y- directions, (while the tool is measuring in the y- and z- directions). Advanced "3D Anisotropy" methods address this by using the Stoneley wave to determine the third axis of anisotropy (Pistre et al. 2005), but this is relatively new technology not yet widely implemented (especially in LWD). Sometimes, however, they y- and z- direction shear is just what we want to understand the layering effects, particularly in unconventional reservoirs. (Pitcher et al. 2011 and Mickael at al. 2012). In high angle wells, the observed compressional velocity isn't the same as the vertical compressional velocity. This is due to **compressional anisotropy** effects. Unlike shear waves, which split into their fast- and slow- components, allowing us to determine the anisotropic velocities, compressional waves will appear as a velocity somewhere between the vertical and horizontal velocities. There is no easy way to correct for this effect, but if several wells in the area have been drilled at different angles, it is possible to use these data to "correct" the compressional data in high angle wells. (Hornby, 2003).

High pressure/high temperature: Since most tools use pressure transducers to measure the formation signal, extremely high pressure can have the effect of attenuating the measured signal enough to adversely affect log quality, particularly high frequency signals, thus we should use tools with high amplitude signals. While temperature affects the reliability of mechanical/electrical systems on the tool, the effect of temperature on the sonic velocity measurement itself is minimal (e.g. no "correction" is needed for temperature).

Anisotropy: While azimuthal sonic tools, such as cross-dipole or imaging tools are capable of characterizing acoustic shear anisotropy, measurements by non-azimuthal tools are influenced by anisotropy but without any azimuthal information they are not able to characterise the anisotropy, yielding some often confusing results. We should be aware of the effects of anisotropy even on standard measurements. An effect commonly seen in LWD non-azimuthal tools (by which we mean the azimuth is not being tracked – obviously the tool still rotates with the drill string) are shear velocities which jump back and forth from one depth to the next (as the tool rotates) or the appearance of double arrivals. This is because the tool will detect the dominant shear velocity(s) in the direction it is pointing when the data were acquired. But without azimuthal info, we can't do much more than observe that a zone is anisotropic.

Table 2 provides a summary of some of the common environmental effects discussed in this section and suggestion to improve data quality under these conditions.

RECOMMENDATIONS BY APPLICATION

In order to acquire good quality sonic data suitable for the target application, we need to understand how the data will be used. Sometimes a classic monopole tool is all that is needed, while for other applications, the most advanced azimuthal imaging tool may be essential. We should also consider how to configure the tool to collect usable data. In this section, we will consider many of the common applications and recommend the type of tool and best configuration for each. While the focus of this paper is not an explanation of how sonic data are used in each application, references are supplied within the text for those who wish to read further.

Environmental Issue	Effect on Data	Mitigation
Large Hole (not necessarily rugose)	Attenuated signal; Leaky-p waves, "Slow Shear" absent	Tools with strong source, sensitive receivers; Large LWD collars; Low frequency;place tool below reamer
Poor Hole Condition (rugosity/wash-out)	Poor signal quality, especially interface modes;	Tools with strong source, sensitive receivers; Stoneley waves for slow shear?
Hole Degradation over time	Poor signal quality, especially interface modes;	LWD tools (earlier measurement); Tools with strong source, sensitive receivers;
Alteration/Invasion	Shallow measurements affected by altered zone	Long-spaced tools; low frequency source
Heavy/Attenuative Mud	Attenuated signal	Tools with strong source, sensitive receivers;
Gas in the wellbore	Attenuated signal	Tools with strong source, sensitive receivers; If LWD, wipe over the interval on the way back out of the hole
Cased Hole	Weak formation response when cement bond bad; difficulty in extracting form. velocities when they are faster than casing	Log open hole with LWD Tools with strong source, sensitive receivers; Low frequency source
Off-centred tools	Dipole, quadrupole data quality suffers;	LWD Tools (less room for eccentring)
Anisotropy	Non-azimuthal tools only measure one direction;	Azimuthally sensitive tools
High Angle Wellbore	Off-centred tools; p-wave anisotropy	See off-centred tools, anisotropy
High Pressure	Attenuated signal; hardware reliability	Select tools with high pressure ratings and good reliability records
High Temperature	hardware reliability	Select tools with high temperature ratings and good reliability records
LWD "Drilling Noise"	Low signal to noise ratio	Place tools away from bit & reamer;wipe intervals with pumps off (or very low)

Table 2. Summary of common environmental effects on sonic logs and suggestions for solutions.

Seismic correlation: Seismic correlation was in fact the original purpose of sonic tools. (Breck et al. 1957). Seismic surveys were common as far back as the 1930's, but time/depth correlation was a problem. Thus, early monopole sonic tools were designed to acquire a compressional velocity log (Vp) to calibrate the seismic surveys. Even today, one of the most common reasons to run LWD sonic tools in exploration wells is seismic correlation. If a standard seismic time/depth correlation is required, then only the compressional velocity (along with density) is needed. We should choose a reliable tool that operates within the expected DTC range. If real-time correlation is needed, then we also need to consider telemetry rates and real-time data monitoring as criteria in selecting a tool/supplier.

AVO (Amplitude Variation with Offset) analysis, the more advanced form of seismic correlation uses compressional and shear velocities (along with density measurements) to more accurately model the seismic response as it varies at offsets away from the wellbore. For AVO analysis, we should choose a reliable tool that operates within the expected DTC & DTS ranges. If possible, we should select a tool capable of measuring shear anisotropy to get the most accurate results. Since AVO interpretation is rarely done real-time, telemetry and real-time processing quality are not critical factors. (Chiburis et al. 1993)

Sonic porosity It may seem old-fashioned now, but before the introduction of neutron-density tools, sonic logs were the primary porosity logs of the industry. (Wyllie, 1956). Even today, sonic logs are still widely used as a primary porosity indicator in environments where nuclear tools aren't suitable and for secondary porosity to identify vugs and fractures. (McCalmont, 2008). The main consideration in choosing a tool for DTC-derived porosity is the operational range. Refer to **Table 1** for which types of tools might be suitable in the target environment. Porosity can also be derived from shear. If these shear porosity methods are to be used, refer to **Table 1** to select a flavour which is likely to acquire a good shear log in the planned well. If real-time correlation is needed, then we also need to use telemetry rates and real-time data monitoring as criteria in selecting a tool/supplier. Azimuthal tools are only needed if azimuthally varying porosity is required, such as in the case of geosteering by porosity.

Pore pressure prediction: Another routine use of sonic data is for pore pressure estimates. (Hottman et al. 1965). One of the main drives for the development of LWD Sonic tools in the 1990's was for real-time pore pressure prediction while drilling. If real-time data is critical, we should choose an LWD provider which can provide reliable sonic tools, good quality real-time compressional curves, and reliable telemetry. We should ensure that the sonic data is being transmitted frequently and that the real-time data are monitored to correct mis-picks by the automatic code. Sometimes, PPP is important but not necessarily needed real-time. A common practice is to run sonic in memory mode (reading and processing the data between runs) or to run wireline at each interval and adjust the drilling plan in between runs. If real-time data is not critical, then we need only focus on getting good quality compressional logs, so we can revert to **Table 1** to select suitable tools for the environment

Wellbore stability and Mud Selection: As acoustic data are sensitive to both pore pressure and stress, they are well suited for wellbore stability and mud selection applications. (Takatoshi et al. 2001) By modelling the response of the formation to the proposed wellbore trajectory and mud properties, we hope to avoid wellbore fracturing or collapse, pack-off, lost circulation, sanding, and stuck pipe. Until recently, most wellbore stability applications used isotropic models, but of late techniques have begun to use more advanced anisotropic models to better predict wellbore failure mechanisms. When choosing a sonic tool for wellbore stability and mud selection, we have to consider the level of interpretation that is expected. For classic computations of a "safe mud window" while drilling the selection criteria are good quality compressional and shear velocities within the expected environment along with reliable telemetry and real-time data monitoring. For more advanced azimuthal wellbore stability applications which use anisotropy to refine the computations, we should select tools that operate within the expected environment and are capable of acquiring azimuthal shear data.

Radial profiling makes use of broadband data to determine compressional and shear slowness and shear anisotropy as a function of distance into the formation. (Sinha et al. 2005) This allows us to see just how far any near-wellbore alteration such as damage, invasion, or alteration by the mud has progressed. More interesting yet, we can compute time-lapse radial profiles during multiple passes over the zones of interest. (Market et al. 2009). To choose a tool which is capable of radial profiling, we need to look for tools which operate in the expected environment and which have broad frequency sources.

Hydrocarbon & Lithology Indicators The VP/VS ratio is frequently used as a lithology and hydrocarbon indicator. (Williams et al. 1990). It is a particularly good indicator of gas, as the compressional velocity moves dramatically slower while the shear is largely unaffected. Unfortunately, even small amounts of gas in the wellbore can significantly affect the signal strength. For non-gas environments, we can use **Table 1** to select tools which can acquire compressional and shear data in the expected slowness range. If gas is a possibility, we should consider using tools with strong, broad frequency sources to have a better chance of detecting the signal despite the gas attenuation.

Permeability: Stoneley data can be used as an indicator of permeability. (Canady et al. 2005). Good quality Stoneley waves are needed, preferably from low frequency monopole data. We can use **Table 1** to select tools which can provide Stoneley data in the expected environment. We should also remember that it the amplitude of the Stoneley waves that are needed (not just the slowness value), so full waveform data are required. There are some caveats to using Stoneley to compute permeability, not least of which is that any hole size variations (wash-outs, break-outs, rugosity, etc.) will mask any sensitivity to permeability. One way to alleviate this is to consider using LWD to acquire Stoneley data, as it is likely to log the formation in the best possible condition, before it has time to degrade. (Tang et al. 2009).

Cement bond Indicator/Top of Cement Another classic application of sonic tools is cement bond characterization. (Grosmangin et al. 1961). The theory is relatively simple – if we observe the amplitude of the wave reflected from the casing, we can estimate the amount of cement bonded to the casing. If the amplitude of the reflection is high, there is little cement. If the amplitude of the reflection is low, then there is cement bonded to the casing which is attenuating the signal. Combining this feature with the character of the formation response through casing, we can estimate the cement bond and identify the top of cement. It is important to note that this is a rudimentary method, not equivalent to an ultrasonic scanning tool designed to provide a map of the cement bond around the casing. Sonic cement bond characterisation methods are not well suited to details such as channelling or the level of cement curing.

Nearly every sonic tool on the market is capable of cement bond analysis. High frequency, shallow source-receiver spacing will give the clearest response of the casing reflection, but broad frequency/multi-frequency tools allow us to also consider the formation response through casing, which can tell us not only if there is cement bonded to the casing, but if there is cement bonded to the formation. Cement bond data can be acquired by wireline or LWD tools. LWD tools habitually acquire data through casing (while tripping in or out of the hole). If we intend to use LWD data for cement logging, we should consider the sample rate vs. tripping speed. Some tools can sample as frequently as once every 2 seconds, which means that to get 1 sample/ft in casing (recommended), we could trip as fast as 1800 ft per hour. Other providers can only go down to 10 second sample rates, so in order to get 1 sample/ft we would need to slow down to 360 ft/hr. In any case, we need to be sure to accurately track depth while tripping in order for the cement log to be valid. While the information can be harvested from data after the fact, in order to optimize acquisition, we should plan for cement bond logging before the run and communicate the preferred tool settings and tripping speed between the service provider and the driller in advance.

Fracture detection/characterization: Sonic data can be used for fracture detection/characterisation at several levels. The **classic method** uses the amplitudes of the compressional and shear waves to indicate the prescience of fractures. (Kokesh et al. 1965). For this type of analysis, DTC and/or DTS slowness and amplitude data are needed. As this is not currently a real-time application, then we just need to select a tool capable of DTC and/or DTS in the expected environment. We can also locate fractures (and other reflectors) using **Stoneley** waveforms. (Brie et al. 1988) We must be careful to distinguish reflections due to formation changes from actual fractures, and the method doesn't give us information about the azimuthal direction of the fractures, but, like the classic methods, can give us indications of the location of fractures. This is also not a real-time application, so we need to choose a tool capable of Stoneley wave acquisition in the expected environment.

If we want to know move more towards characterizing fractures (rather than just identifying them), we can use **azimuthal shear logging** tools (cross-dipole or imaging tools) to determine the shear velocity around the wellbore. We can then relate those velocities to stresses around the wellbore and then derive fracture information such as direction of the fracture, magnitude, and whether it is open or closed. Broad frequency tools allow us to perform these interpretation both in the near wellbore and deeper into the formation, yielding information about whether the fractures are drilling induced and/or intrinsic (and possibly even both). (Sinha et al. 2005). These are not real-time applications, and do require a considerable level of expertise to interpret the results correctly. We should choose azimuthal shear logging tools that work within the expected environment. We should also ensure that the processing is done by experienced analysts. Finally, **Deep fracture imaging** is a processing-intensive method but can yield information about fractures/reflectors 30+ metres into the formation. (Tang et al. 2010). This analysis requires cross-dipole wireline tools and expert processing.

Production optimization We can use basic compressional and shear data to select optimal production zones, but if we have azimuthal shear data, we can also optimize the orientation of the production. For the former, we can select any tool which operates within the expected environment, while for the latter, we need to use azimuthal shear tools that operate within the expected ranges.

Geosteering: While it is much more common to geosteer with resistivity or gamma ray, in cases where these techniques aren't practical (i.e. when there is little or no contrast in the resistivity of surrounding layers), sonic can offer a complementary method for geosteering. For example, in carbonate reservoirs with wet zones, there may be too little resistivity contrast to steer reliably, but it is quite likely that the porosity contrast can still be seen by the sonic measurements. (Pitcher et al. 2011). To effectively geosteer, we need to choose LWD azimuthal tools which are reliable within the expected environment. Both telemetry and real-time data monitoring are also key factors to consider when choosing a service. Since this is a relatively new application, detailed planning and real-time monitoring of the data is essential.

Unconventional Reservoirs. One of the more recent applications of azimuthal shear data is in unconventional reservoirs. (Mickael et al. 2012). By measuring the compressional azimuthal shear velocities around the wellbore, we can distinguish brittle and ductile zones and select the optimal zones for production. We can even geosteer by brittleness. Azimuthal LWD tools are required for “steering to the zone” but non-azimuthal LWD or wireline tools will still see the splitting of the shear and it is possible to select the optimal zones from the logs, even if the direction of the dip must be determined from other measurements

Hole Size/Shape: Using sonic waveform data for a hole size indicator was one of the early applications (Kokesh et al. 1965) which has largely been forgotten with the availability of modern mechanical and ultrasonic calliper tools. Recently there has been a resurgence of interest in alternative hole size methods for such application as cement volume calculations in large holes where more mechanical callipers and ultrasonic devices aren’t effective. (Market et al. 2011). While far from a true “calliper”, we can derive a hole size indicator from sonic in most environments (troublesome cases are very slow formations where leaky-p waves tangle with DTC). We can use the compressional or refracted shear arrivals. Thus, we need to select a tool capable of logging DTC or DTRS in the expected environment. Because we generally don’t know the centralization/position of the collar in the wellbore, we should select a tools with multiple axial receiver arrays to get a better estimate of hole size (rather than just stand-off). If we want to gleam some information about hole shape, we should select tools with azimuthal capabilities.

Table 3 summarises the sonic data selection criteria for selected applications.

	DTC	DTS	Stoneley	Shear Anisotropy	DTC, DTS Images	Other	Special Configuration
Seismic Time/Depth Correlation	✓						
AVO	✓	✓		*			
Porosity	✓	*					
Pore Pressure Prediction	✓						
Hydrocarbon Detection / Lithology Indicator	✓	✓					
Cement Bond/Top of Cement	*					Casing Amplitude	
Permeability	*	*	✓			Stoneley Amplitude	
Fracture Detection (classic P&S)	✓	✓				DTC, DTS amplitudes	
Fracture Detection (Stoneley reflectors)	*	*	✓			Full monopole waveforms	
Fracture Characterisation (anisotropy)	*	✓		✓			
Deep Fracture Imaging	*	✓	*	✓		Full waveforms	Configure tool to listen long
Classic Wellbore Stability	✓	✓					
Anisotropic Wellbore Stability	✓	✓		✓			
Production Optimisation – Basic Zone Selection	✓	✓					
Production Optimisation – Direction	✓	✓		✓			
Geosteering	✓	*			✓	Need DTC or DTS Images – not necessarily both	Check with vendor minimum ROP requirements
Unconventional Reservoir Optimisation	✓	*	*	*			
Hole Size Indicator	✓	*				Need DTC or DTS Full Waveforms required	

Table 3. Summary of which types of data are needed for various applications to aid in selection of a sonic tool/service.
✓Data required
* Data optional – it will improve the results but is not absolutely essential.

SUMMARY - CHOOSING THE RIGHT SONIC SERVICE

Not only are the physics of borehole acoustics complex, but choosing the right service for a particular environment and application can be dizzying as well. **Figure 3** illustrates some of the many factors we must take into account when planning a sonic data acquisition programme. We should consider hardware (tool functionality & reliability) as well as data processing and interpretation quality. If the primary application is a real-time one, then we must prioritise hardware reliability, telemetry, and data processing. If we are using the data for a high-end expert application, then we must consider data quality, processing ability, and the accessibility of the processor for handling enquiries about the data interpretation. If we are trying to choose between wireline and LWD options, we need to weigh conveyance risk, tool and rig time cost, and appropriateness of the tool for the application.

Whichever tool and processing service we select, the end user, tool provider, and data analyst should be involved early in the planning stage to increase the chances for success. The deliverables should include the full waveform data and acquisition parameters along with clearly labelled processed data and interpretation reports. Who knows what new application may be developed tomorrow? If the data are archived in good order, we may be able mine treasures out of the waveforms for many years to come.

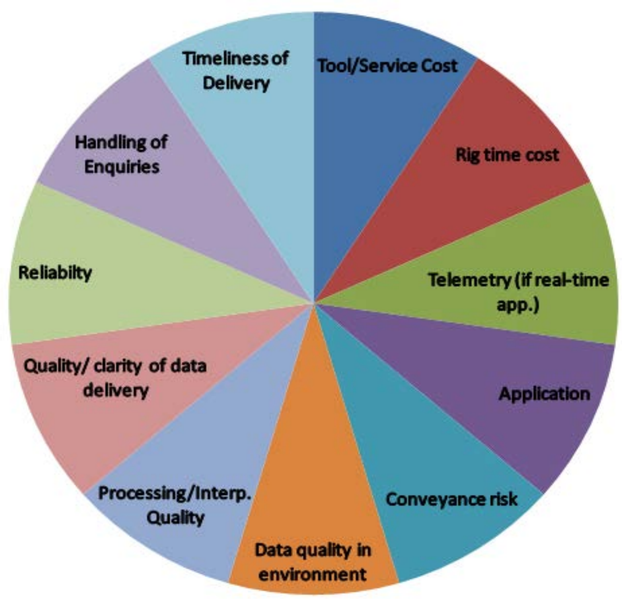

Figure 3. Balancing the criteria to select a sonic service

ACKNOWLEDGMENTS

The author wishes to thank Craig Barnett, Wyatt Canady, Bill Langley, John Walsh, and Doug Patterson for their willingness to provide assistance.

REFERENCES

Blyth, M., Alford, J., Tollefsen, E., Pelorosso, M., 2012, "A new standard in real-time LWD sonic capability: Improving confidence in critical wellbore stability and formation evaluation decisions," SPWLA 53rd Annual Logging Symposium.

Breck, H.R., Schoellhorn, S.W. and Baum, R.B., 1957, "Velocity Logging and Its Geological and Geophysical Applications," Bulletin of the American Association of Petroleum Geologists, 41, no 8, pp 1667-1682.

Canady, W., Spooner, P., Vasquez, R., 2005. "Permeability Estimation From Stoneley Amplitude, Corrected for Borehole Geometry and Rugosity", SPE96598.

Brie, A., Hsu, K., Eckersley, C., 1988, "Using the Stoneley Normalized Differential Energies for Fractured Reservoir Evaluation", 29th SPWLA Annual Logging Symposium.

Chiburis, E., Leaney, S., Skidmore, C., Franck, C., McHugo, S., 1993, "Hydrocarbon Detection with AVO", Oilfield Review, Jan 1993.

Dubinsky, V., Tang, X.M., Bolshakov, A., and Patterson, D., 2003," Engineering aspects of LWD Quadrupole Measurements and Field Test Results", SPE 84248.

Grosmangin, M., Kokesh, P.P., Majani, P., 1961, "A Sonic Method for Analyzing the Quality of Cementation of Borehole Casings", SPE-1512.

Harrison, A.R., Randall, C.J., Arron, J.B., Morris, C.F., Wignall, A., Dworak, R.A., Rutledge, L.L., and Perkins, J.L.,1990, "Acquisition and Analysis of Sonic Waveforms from a Borehole monopole and Dipole Source for the Determination of Compressional and Shear Speeds and their Relation to Rock Mechanical Properties and Surface Seismic Data", SPE 20557.

Hornby, B.E., Howie, J.M., Ince, D.W., 2003, "Anisotropy correction for deviated well sonic logs: application to seismic well tie", Geophysics, 68, 464-471.

Hottman, C.E. and Johnson, R.K., 1965, "Estimation of Formation Pressures from Log-Derived Shale Properties", Journal of Petroleum Technology 17, no. 6, pp 717-722.

Kokesh, F.P., Schwartz, R.J., Wall, W.B., Morris, R.L., 1965, "A New Approach to Sonic Logging and Other Acoustic Measurements", SPE 991.

McCalmont, S., Chittick, S. Nurgaliev, R., Russo, J., Deady, R., Market, J., 2008, "Optimal FE Acquisition in a Complex Carbonate Reservoir: a Case Study on the Karachaganak Field, Kazakhstan", SPWLA 49th Annual Logging Symposium.

Market, J., Hauser, M.R., Althoff, G. Deady, R.J., Varsamis, G.L., 2002, "LWD Sonic Logging in Large Diameter Surface Holes", SPE 77480.

Market, J., 2006, "Dispersion Corrections Are Not Just for LWD Dipole Sonic Tools", SPE 102345 (2006).

Market, J., 2007, "Broad Frequency LWD Tools Provide High Quality Compressional and Shear Data in a Wide Variety of Formations", 48th SPWLA Annual Logging Symposium.

Market, J., Canady, W., Elliot, P., Hinz, D., 2009, "Wellbore Profiling with Broadband Multipole Sonic Tools", SPE 123865.

Market, J. and Canady, W., 2009, "Multipole Sonic Logging in High Angle Wells", SPWLA 50th Annual Logging Symposium.

Market, J., Bilby, C., 2011. "Introducing the First LWD Crossed-Dipole Imaging Service", SPWLA52nd Annual Logging Symposium.

Market, J. And Parker, T., 2011. "Reliable LWD Callipers", SPE 146245.

Mickael, M., Barnett, C., Diab, M., 2012. "Azimuthally Focused LWD Sonic Logging for Shear Wave Anisotropy Measurement and Borehole Imaging", SPE160133.

Minear, J., Birchak, R., Robbins, C., Linyaev, E., Mackie, B., Young, D. And Malloy, R., 1995, "Compressional Slowness Measurements While Drilling", SPWLA Annual Logging Symposium, 1995.

Pistre, V., Kinoshita, T., Endo, T., Schilling, K., Pabon, J., Sinha, B., Plona, T., Ikegami, T., Johnson, D., 2005. "A Modular Wireline Sonic Tool for Measurements of 3D (Azimuthal, Radial, and Axial) Formation Acoustic Properties", SPWLA 46th Annual Logging Symposium.

Pitcher, J., Market, J., Hinz, D., 2011. "Geosteering with Sonic in Conventional and Unconventional Reservoirs", SPE 146732.

Plona, T.J., Sinha, B.K., Kane, M.R., Walsh, J., Viloria, O., 2000, "Using Acoustic Anisotropy", paper RR, presented at 41th Annual SPWLA Symposium, Dallas Texas USA.

Sinha, B., Kane, M.R., Frignet, B., 2000, "Dipole Dispersion Crossover and Sonic Logs in a Limestone Reservoir", Geophysics 66, no 2, pp 390-407.

Sinha, B., Vissapragada, B., Kisra, S., Sunaga, S., Yamamoto, H., Endo, T., Valero, H.P., Renlie, L., Bang, J., 2005. "Optimal Well Completions Using Radial Profiling of Formation Shear Slownesses", SPE 95837.

Takatoshi, I., Zoback, M.D., Peska, P., 2001, "Utilization of Mud Weights in Excess of the Least Principal Stress to Stabilize Wellbores:Theory and Practical Examples", SPE Drilling and Completion, December 2001.

T**ang**, X., Patterson, D., Wu, L., 2009, "Measurement of Formation Permeability Using Stoneley Waves from an LWD Acoustic Tool", SPWLA 50th Annual Logging Symposium.

Tang, X., Bolshakov, A., Patterson, D., 2010, "Integrated Acoustic Evaluation of Reservoir Fractures: From Borehole Out into Formation", SPWLA 51st Annual Logging Symposium.

Varsamis, G., Wisniewski, L., Arian, A., and Althoff, G., 1999, "A New Full Wave Dual Mode Sonic Tool Design and Case Histories", SPWLA 40th annual logging symposium, May 30-June 3, 1999.

Wang, T., Dawber, M., Boonen, P., 2011, "Theory of Unipole Acoustic Logging Tools and their Relevance to Dipole and Quadrupole Tools for Slow Formations", SPE 14515.

Williams, D.M., 1990. "The acoustic log hydrocarbon indicator", SPWLA 31st Annual Logging Symposium, paper W.

Wyllie, M.R.J., Gregory, A.R., and Gardner, L.W., 1956,"Elastic Wave Velocities in Heterogeneous and Porous Media", Geophysics 21, no 1, pp 41-70.

ABOUT THE AUTHOR

Jennifer Market is the borehole acoustics manager for Senergy, an international software and consulting company. She has 15+years' experience in borehole acoustics, working in a service company to develop acoustics tools and applications. She frequently publishes articles for both SPWLA and SPE and was an SPWLA distinguished lecturer in 2008-2009 and 2011-2012.