Next Generation Borehole Seismic Source: Dual-Wavefield Downhole Vibrator System

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SUMMARY

Recent advances in crosswell seismic technologies have lead to the successful development and release of a new downhole seismic source that imparts greater energy into the formation by sweeping frequencies in the range of 30-800 Hz. The result is, for the first time, a powerful, efficient and cost effective vibrator for use in the borehole allowing for enhanced seismic imaging between wells up to 2km apart.

In addition, the patented design and operation of the source allows for both compressional and shear wave energy to be acquired simultaneously along with the flexibility of being able to acquire data in reverse vertical seismic profile configuration.

Crosswell imaging is a technique that has been in practice for the past 15 to 20 years and much has been published about the traditional downhole sources that have been used which include electrical sparkers, weight drops and piezo ceramic vibrators. With these high frequency transmitters, several inherent factors have impeded the application in well separations greater than 1 km and hence wider acceptance in the seismic imaging options available for field development. These factors are attenuation of the higher frequencies, different frequency bandwidth from surface seismic and lack of direct shear wavefield content.

	Airguns/Explosives	PiezoElectric	Sparker
Frequency Range	50Hz to 2000Hz	300Hz to 4000Hz	50Hz to 2000Hz
Well Spacing	Up to 1km – Limited by hole damage	Up to 1km in High Velocity Rocks	500m
Limitations	Casing damage, Tube waves, output changes with depth	Poor low frequency output and Tube waves	Slow repetition and Tube waves

Figure 1: Traditional downhole seismic sources, frequency content and maximum inter-well imaging distance.

This paper discusses key features of a newly developed downhole seismic source (Z-Trac^{TM}) that helps address the challenges stated above. This magnetically clamped source is intended specifically for formations with high attenuation and large distances between wells. Operating at a lower frequency range (30 Hz–800 Hz), this source produces about 20 dB more amplitude than current piezoelectric sources. It also produces direct compressional and shear energy waves, allowing for advanced wavefield analysis. It distributes the energy produced over an area in the wellbore that is large enough not to cause damage to the casing or cement.

Results from recent case studies are also presented to highlight the benefits being seen in various applications from around the world. Brief descriptions of the acquisition and processing methodologies are also referenced as a background to the case results shown.

METHODOLOGY

Crosswell Seismic Acquisition

The source is lowered into one well and a receiver array or arrays are lowered into one or more adjacent wells. High frequency sound, typically 30 to 800 Hz, is transmitted into the reservoir by the source. The energy created is recorded at the receiver well(s). The goal is to illuminate as much of the subsurface as possible through the aperture of the source locations and range of receiver locations. In a typical acquisition both source and receivers are placed at the base of the reservoir or zone of interest. The source is raised and pulsed until the entire zone is imaged at that receiver station. The receivers are raised to the next station, the source is lowered to the base of the reservoir, and the pulsing process is repeated. Once complete, several profiles of raw data are acquired and processed. The base of the reservoir image is filled in using reflection tomography.

Two types of information are acquired and processed on a routine basis: First, the direct arrival between source and receivers is used to create a 2-D map of seismic velocity, and second, reflection information from horizons above and below the source and receiver positions is used to create a structural image between wells (Fig. 2). In addition, there are many other modes and attributes of the crosswell seismic data field that can be captured and processed to yield specific information about the subsurface, such as guided waves and converted waves. The combined velocity and reflection profile provides not only detailed information about the structure of a given reservoir, but also the properties of the rock contained in it.

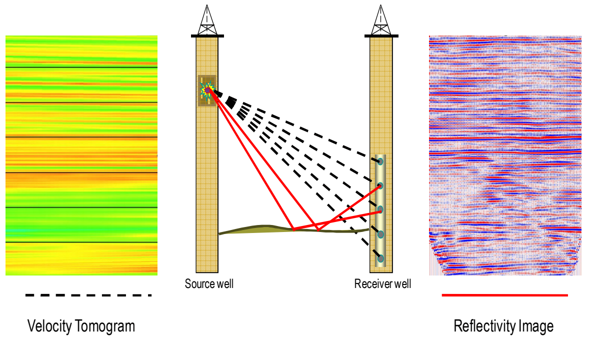

Figure 2: Data are acquired by having a receiver string recording seismic signals from a source deployed in another well. This allows for velocity (dashed black) and reflection (solid red) imaging to be processed.

Detailed feasibility assessment and modeling are conducted to qualify the value and applicability of crosswell seismic in an application based on specific well and field conditions and deployment options.

Crosswell Seismic Data Processing

The processing flow for crosswell seismic is made up of three major steps; tomographic processing, reflection processing and reflection imaging. Crosswell seismic processing methods are a hybrid of multi-fold techniques used in surface seismic processing and wavefield separation and imaging methods from VSP data processing. Unique to crosswell seismic is the tomographic inversion process that uses direct arrival travel times and reflected travel times to produce a profile of seismic velocity. The seismic velocity field from the tomographic inversion also serves as the high-precision velocity model for reflection imaging.

Data are prepared for reflection imaging with a sequence of wavefield separation processes. Wavefield separation refers to removing arrivals present in the crosswell data set other than the desired reflection events. Arrivals that are selectively removed include tube waves (fluid borne energy in the source or receiver wells), the direct arrival and downgoing reflections. A significant advantage in crosswell seismic data is the high stack fold available for stacking the reflection data. Stacking attenuates many of the unwanted arrivals in crosswell data. Based on processing experience, a few wave modes are typically removed in wavefield separation. Other modes may be selectively removed based on their unwanted contribution to the stacked image.

Just as with surface seismic, crosswell seismic data sets contain reflection information from impedance contrasts in the subsurface layering of the earth which can be used to map geologic stratigraphy and structure. Various methods can be applied to the imaging of crosswell reflection data. Either a VSP-CDP mapping followed by a pre-stack, post-map migration is applied or a pre-stack, pre-map Kirchhoff migration to produce the reflection image is run.

KEY FEATURES & RESULTS

Improved Source Strength

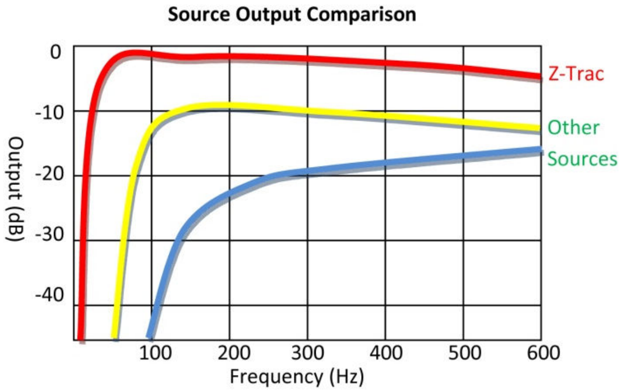

Figure 3: Comparison of the new Z-Trac™ energy output with existing sources.

Dual Wavefield Seismic

The source output is directional with P wave strongest along the primary axis and shear output perpendicular to the primary axis. To eliminate the need for known source orientation, two source axes are deployed oriented at 90° to each other. The received data from the two axes are then rotated and combined to produce a P wave data set where the primary axis points at the receiver and an S wave data set where the primary axis points 90° to the receivers.

Z-Trac™ data recorded with a 3-component (3C) receiver is effectively a 6-component data set. A data rotation operation is performed on the horizontal components of the data and 2 horizontal components of the 3C receiver to produce an inline (source and receiver rotated to the line between the wells) and crossline (orthogonal) horizontal component of data. Figure 4 shows an example of a dual wavefield common receiver gather (receiver at a point in depth with data generated from several source positions). Similar images are also viewed in common source format.

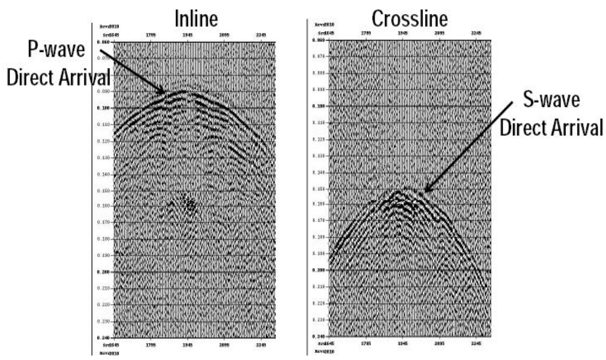

Figure 4: Dual wavefield data set with P-wave data (left) and S-wave data (right). The data represents a common receiver gather with receiver at a measured depth 2010 m. The source depths range between 1645 m and 2435 m. The X-axis represents increasing source depth and y-axis shows time in (ms).

Wellbore-Safe Transmission

Since this new source distributes its energy output over 3 to 4 metres of the wellbore and is operated in a swept frequency mode to further distribute its energy output over time, the source has essentially no potential for damaging casing or cement. The very low risk of damage to cemented boreholes by the source is primarily due to its asymmetrical coupling and lateral dynamic vibration in cased wells. The method of coupling to the casing differs significantly from that of air gun and explosive charges which generate high impulsive pressures in liquid-filled casings.

The source nevertheless can radiate the same or a greater amount of seismic wave energy as an air gun or explosive source by generating its relatively low vibratory source signal over an extended time period in the form of a controlled-waveform frequency sweep.

The low vibratory stress of the Z-Trac^{TM} source is achieved by distributing the output force over the relatively long active length of the tool. The most vulnerable cement failure problem associated with Z-Trac^{TM} operation is recognized to be the stress relief action on the trailing side of the lateral casing motion. To prevent tensile failure in the cement or in its interface bonds, the formation overburden preload stress must always be greater than the stress relief caused by the moving casing. This constraint requires that the Z-Trac^{TM} tool must be operated at downhole depths, Z_T at which the formation overburden pressure is greater than the dynamic stress produced by the tool. That is, neglecting the small tensile strength of the cement, the minimum operating depth of the Z-Trac^{TM} tool is:

$$Z_T = \frac{F_v}{A_v \Delta P_f} = \frac{2{,}400\ \text{lbf}}{240\ \text{in}^2 \cdot 1.08\ \text{psi/ft}} = 9.3\ \text{ft}$$

Figure 5: Operating depth parameterisation for Z-Trac^{TM}.

This very modest minimum operating depth indicates that there is no practical risk of damage to cemented wellbores associated with Z-Trac^{TM} tool operation.

Reverse Vertical Seismic Profiling

By having a more powerful downhole source, a new and practical acquisition configuration is possible. Reverse vertical seismic profiling (RVSP) makes use of the downhole source by deploying surface receivers in areas where legal/logistic limitations prevent the deployment of conventional methods.

The added advantage of RVSP is reduced near source noise and potentially higher resolution as a result of the higher frequency bandwidth of the downhole source. To date several experimental surveys have been conducted and work towards understanding the optimum parameters for acquisition is ongoing.

Figure 6 is an example of a data set using a maximum surface spacing of 350m from the borehole with the source deployed to a depth of approximately 1000m.

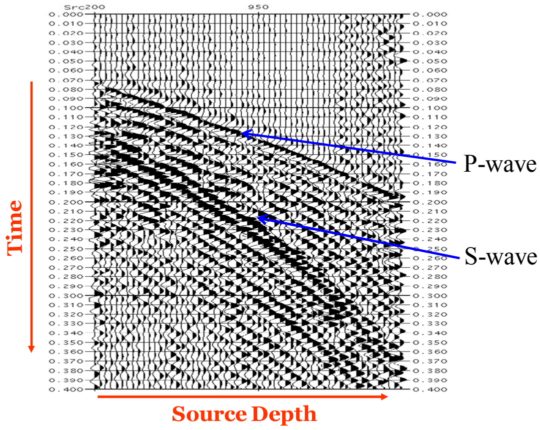

Figure 6: Reverse VSP data from a clastic onshore US field showing P and S energy.

Record Interwell Spacings

To illustrate the capability of this source, a case study from Indonesia is referred to in the following paragraph in which the surface seismic was not able to adequately image the subsurface. This magnetically clamped source was used to reveal the region between wells. The project also was the site for world record well spacing for crosswell seismic in a very challenging, highly attenuative formation. The frequency range employed for the project was from 30 to 200 Hz, adequate for enhanced imaging in the formation.

The formation is dominantly sand-shale formations with intercalations of coal seams. Seismic interpretation becomes increasingly difficult as the surface seismic is not of high quality. Structurally, the acquisition area encompasses several major faults that create sub horst-graben features. Crosswell seismic was acquired over eleven (11) profiles covering most parts of the field to help in refining the seismic interpretation and potentially to reduce the uncertainty in infill drilling decisions. The results of two profiles are shown in Figure 7. The seismic sections generated clearly show remarkable improvement over the existing seismic despite high seismic attenuation observed in this area (Dogra et al., 2011).

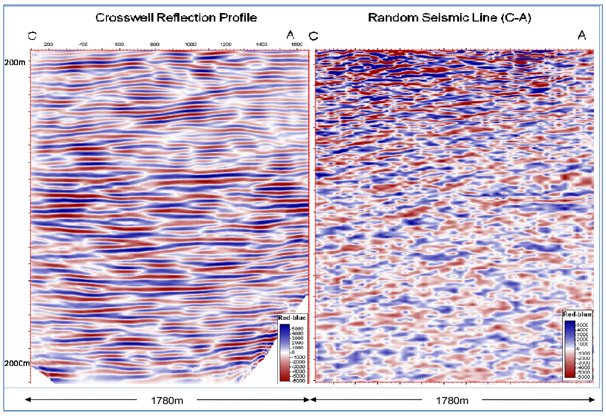

Figure 7: Crosswell seismic reflection section (left) at world record spacing of 1780m compared with equivalent surface seismic extraction in the same plane from the 3D cube (right).

CONCLUSIONS

Significant advances have been made in making this downhole seismic source technology more usable and adaptable to the growing challenges in the industry today. The case studies have clearly demonstrated that these new advances show immense promise and potential in addressing the complex questions that many operators have in optimising operations and adding new interwell information to enhance field development

ACKNOWLEDGMENTS

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