Copenhagen | '12

E043

The Potential of Single-well Acoustic Imaging for Detecting the Direction and Distance to a Target Borehole

M.A. Jervis* (Saudi Aramco), A.V. Bakulin (Saudi Aramco), T.L. Tonellot (Saudi Aramco), I.A. Ghamdi (Saudi Aramco), A. Shabbir (Schlumberger) & H. Yamamoto (Schlumberger)

SUMMARY

A new method to locate nearby boreholes using acoustic imaging is presented. The challenge of locating a nearby well from a borehole is commonly addressed with electromagnetic (EM) or passive magnetic ranging methods, which can suffer from poor resolution and penetration and require the presence of a conductive or magnetic casing. Single-well acoustic imaging has great potential for locating a nearby borehole at higher resolution and with fewer of the limitations of EM-based methods. Acoustic imaging requires only an impedance contrast between the target object and the formation, which is adequately provided by the presence of a fluid-filled borehole. Two tests are shown demonstrating the capabilities of the new method. In the first test, a vertical borehole is located and imaged from a nearby horizontal well, and in the second test, a vertical borehole is imaged from a nearby near-vertical well. In both cases the estimated distances were validated by independent measurements.

Introduction

Single-well imaging using full-waveform sonic log data (Figure 1a) is a well-known technique for locating fractures and mapping bed boundaries at distances up to 60 ft (18m) away from the well (Hornby 1989; Esmersoy et al. 1998). The design of many modern acoustic tools allows their usage for single-well imaging without any modifications to the actual tool; all that is required is a longer listening, or recording, time. One challenge for single-well imaging using a sonic tool is the separation arrivals from different directions. This separation can be more easily achieved if the source frequencies are sufficiently high relative to the size of the tool, and wavelengths should be on the order of the radial receiver separation. In this study, the sonic tool used comprised 13 receiver levels each equipped with eight azimuthal piezo-electric sensors spaced every 45° around the tool's circumference. This configuration allows performing analysis of the signal along different azimuths and detecting the approximate direction of the arrivals (Haldorsen et al. 2006).

To perform sonic imaging in a realistic 3D environment with an arbitrary borehole deviation, the tool and consequently all the receivers are oriented in space by measuring tool azimuth and inclination. After applying noise-removal techniques on the data to remove P- and S-wave refracted arrivals and Stoneley waves and performing migration, images can be obtained at extremely high vertical resolution (<0.3 m) using different sets of azimuthal receivers to separate arrivals from different directions. The migrated images offer information about the fine structure of the reservoir up to 50 ft (15m) away from the borehole to help identify near-borehole bed boundaries as well as fractures and faults. Here we demonstrate a novel use of the same techniques for locating nearby wells in two case studies.

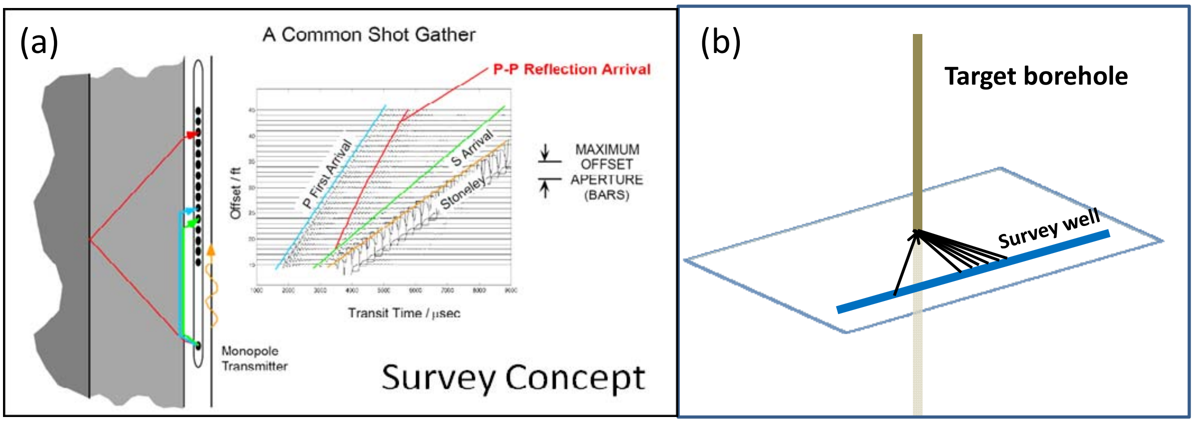

Figure 1 *The single-well imaging concept showing a) direct and reflection arrivals on the sonic data and b) a schematic of the well configuration used in the first example. It is preferable to select appropriate offsets where reflected events occur in a relatively quiet, noise-free time window that does not overlap with strong guided wave arrivals such as Stoneley waves, which travel along the borehole.*

New application

Current industry practice for locating a borehole is to use active EM and passive magnetic ranging methods. These methods rely on electric and magnetic properties of the target casing and therefore would not work for boreholes that are uncased or cased with non-magnetic or non-conductive material. In addition, magnetic methods generally have much lower spatial resolution than seismic methods and can have much shorter detection distances, particularly where the target object is perpendicular to the orientation of the magnetic survey direction causing poor EM coupling.

Here an alternative approach is introduced using acoustic measurements that can work for both cased and uncased targets in any orientation. It is also demonstrated that in certain configurations the accuracy of the acoustic measurements can be considerably higher than that of EM methods. In an ideal scenario, combined usage of both approaches would provide a more reliable answer with less overall uncertainty.

Example 1: Locating a vertical well from a nearby deviated well

In the first example, full-waveform sonic data was acquired to locate a nearby cased vertical borehole from a near-horizontal observation well (75^{o} deviation) (Figure 1b). It was envisaged that the high signal frequencies, and hence short wavelengths relative to the tool diameter, would make the diffracted energy from the target well detectable by azimuthally distributed receivers, which would provide a direction to the well. The tool has a maximum source-receiver offset of 17 ft (5.2 m). To provide the best possible conditions for the sonic tool, the observation well was purposely drilled to pass the vicinity of the target well in a relatively massive high-velocity anhydrite formation (20,000 ft/s [6100 ms/]). This environment would provide a formation with low attenuation, hence good signal strength. In addition, the absence of major nearby reflectors or complex geology would simplify data processing.

The pre-stack waveform data (Figure 2a) shows a clear diffraction at the location along the borehole indicated from passive magnetic data acquired during drilling. In this case, the diffraction energy arrived between the P- and S-wave refracted arrivals. If the event can be seen on pre-stack data, the analysis is straightforward. The apex of the diffraction hyperbola gives the location along the borehole at which the target well is closest to the observation well. The travel time at the diffraction apex gives the shortest distance between both wells using the P-wave velocities measured using the same sonic log. To determine the direction to the target borehole, azimuthal variations in the signal are used (Figure 2b). The distance to the target from the pre-stack waveform data was estimated to be about 9 ft (2.7 m). Small errors in the location arise from inaccuracies in the time picks as well as any small velocity variations away from the borehole.

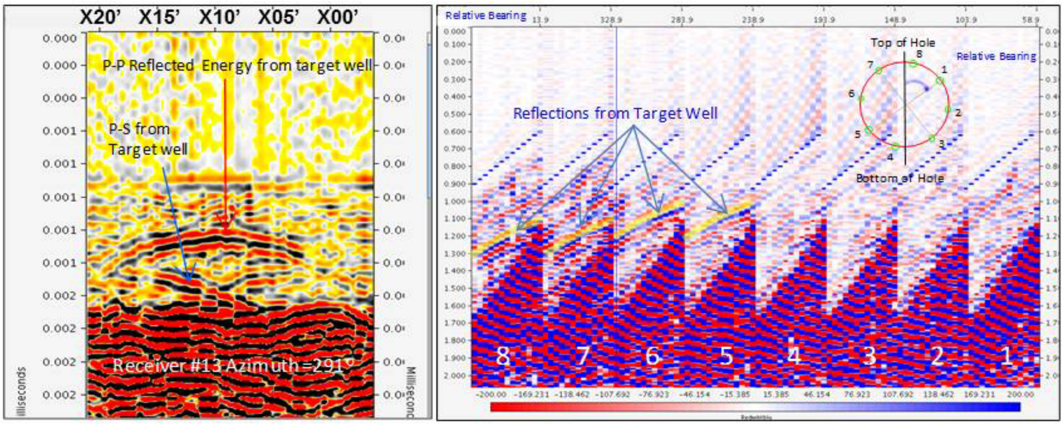

***Figure 2** Pre-stack sonic log data after filtering of the P-wave showing a) common-receiver gather for the far sensor at 13 ft (4 m) offset and (b) the corresponding shot gathers (after removing P-wave head arrivals) for eight azimuthally distributed receivers. The expected moveout of P-wave diffracted energy is clearly visible only on receivers 5 to 8 indicating they are facing the target direction.*

In addition to the diffraction analysis, a pre-stack depth migration image was also produced using the formation velocities. Figure 3 shows the results from migration of the input data after noise attenuation. Note that up- and down-going reflections are present, but the borehole reflection/diffraction is actually from adjacent to the survey well but is imaged in the same plane as vertically travelling energy. The target well is clearly imaged as a point that can be accurately located 9 ft (2.7 m) from the observation well with even less error than the pre-stack diffraction analysis. This distance was confirmed by drilling a side track well that hit the target. Results obtained with passive magnetic ranging data while drilling (MWD) confirmed the location of the magnetic anomaly, but provided much less accurate distance-to-target estimates than the acoustic data in this configuration.

In addition to detecting and imaging the target well, the migration section shows clear bed boundaries up to 100 ft (30 m) above and below the well track. This is the deepest imaging depth achieved to date using full-waveform sonic data. This success is due mainly to the high velocity and correspondingly low formation attenuation minimizing energy loss with distance for the seismic signal.

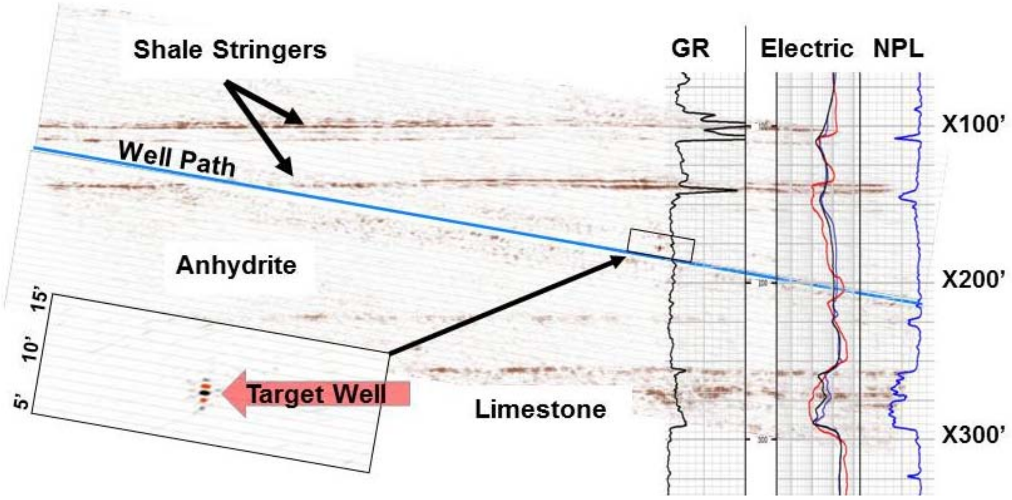

Figure 3 *The results from phase-shift migration of the pre-stack data after noise removal showing reflectors up to 100 ft (30 m) above and below the well where the sonic data was acquired. The image shows excellent agreement with gamma-ray, electric and neutron-porosity logs from the nearby vertical well. The location of the nearby well is marked by the red arrow. An expanded view shows the target borehole at 9 ft (2.7 m) from the observation well.*

Example 2: Locating a vertical well from a nearby vertical well

In a second test, the objective was to detect a cement-filled vertical cased borehole from a nearby sub-vertical well (Figure 4a). Even though the formations here are horizontal as in the first test case, they exhibit large vertical velocity variations (Figure 4b). Whereas in the previous example the target well was fluid-filled, in this example the target borehole was cemented, reducing the impedance contrast between the formation and the wellbore. Well survey and magnetic ranging data indicated that the target borehole was about 20 to 25 ft (6 to 7.5 m) from the observation well. Due to the larger distance to the target, it was expected that reflected/scattered energy from the well would be much weaker and arrive in the same time window where strong refracted S-waves are recorded. The generally lower formation velocities and consequently higher attenuation in these formations further reduce the reflection signal strength. As an added complication, reflections from the target in this configuration are expected to have similar moveout over the source-receiver offset as the refracted P-, S-waves and Stoneley arrivals in the common offset/receiver gathers. Hence this configuration makes noise removal without damaging the reflected events more challenging. Therefore unambiguous identification of the reflected energy was not possible on pre-stack data. Nevertheless, after noise removal on the common shot gathers and migration, an image was obtained that is generally consistent with the expected location of the target borehole (Figure 4c). The high-amplitude red event in the lower section is interpreted as an image of the target well even though it seems close to the band of migrated residual S-waves seen as the blue area in the section above. If the red event were simply migrated residual shear waves, then there would no reason for it to decay in amplitude in the section above. The migrated image shows that the high-energy event is present only in the lower section where a relatively fast limestone is located. This suggests that the acoustic impedance contrast between cement-filled borehole and formation is sufficiently high in the fast formation but too low in the slow formations above to generate a visible reflection. Since the strength of scattered signal is proportional to the impedance contrast, and the migration image strength is consistent with the P-wave velocities from log data, this suggests that the observed event is real and not an artifact.

Based on the borehole velocity profile and picked arrival times of the reflected event, the distance to the target well is estimated to be 21 to 23 ft (6.4 to 7 m) from the survey well (Figure 4c). These distances are in close agreement with those estimated from gyro surveys of both wells as well as the results from active EM ranging from the same well.

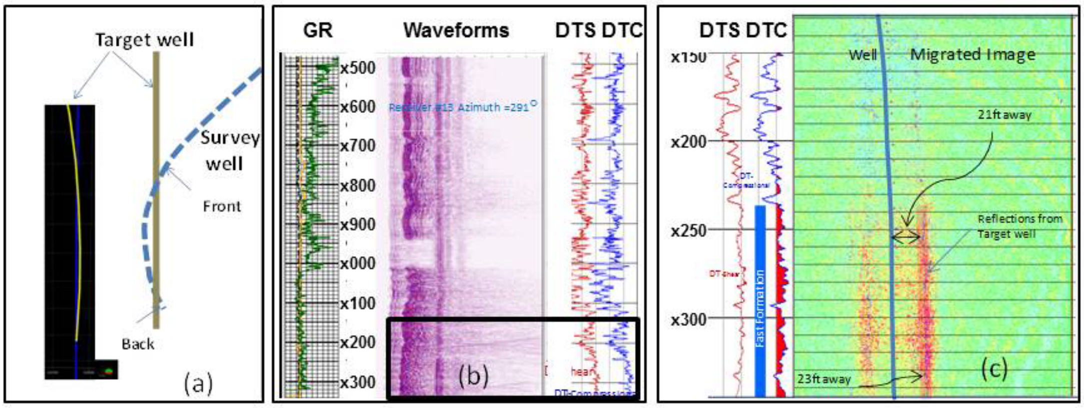

Figure 4 *The second example showing a) the sub-parallel well configuration, (b) a common-receiver gather for the far-offset sensor (13 ft [4 m]) and associated P-wave (DTC) and S-wave (DTS) slownesses, and (c) the migrated image. The black box indicates the depth range used in the migrated image. The high-amplitude (red) migrated event is interpreted to be an image of the target borehole.*

Conclusions

Two tests were presented validating a new application of single-well acoustic imaging for detecting the direction and distance to a target borehole. It has been shown that in an orthogonal borehole to borehole configuration in a relatively homogeneous formation single-well imaging can reliably detect a fluid-filled cased target borehole with low uncertainty with performance significantly better than passive magnetic ranging. Unlike passive magnetic MWD measurements, but like active ranging it does require an additional trip in the borehole to acquire the data. In a parallel borehole configuration the imaging suffered from vertical heterogeneity, but still detected a cemented target borehole in a portion of the well where significant acoustic impedance contrast was present. This result was consistent with active electromagnetic ranging results. Acoustic and EM measurements respond to different physical properties and therefore have a complementary nature: single-well imaging can detect boreholes without magnetic or conductive casing, whereas electromagnetic tools can detect cemented cased boreholes that have little acoustic contrast with surrounding formations. It is recommend to apply both approaches and jointly interpret the results to reduce the uncertainty inherent in any single measurement. Modelling is planned to better understand and process the different measurements, and to develop an efficient joint inversion method.

Acknowledgements

The authors would like to thank Saudi Aramco for permission to publish this work.

References

Esmersoy, C., Chang, C., Kane, M., Coates, R., Tichelaar, B. and Quint, E. [1998] Acoustic imaging of reservoir structures from a horizontal well. *The Leading Edge*, **17**(7), 940–946.

Haldorsen, J. B. U., Voskamp, A., Thorsen, R., Vissapragada, B., Williams, S. and Fejerkov, M. [2006] Borehole acoustic reflection survey for high resolution imaging. *76th SEG Annual International Meeting*, Expanded Abstracts, 314–318.

Hornby, B. E. [1989] Imaging of near-borehole structure using full-waveform sonic data. *Geophysics*, **54**, 747–757.