

HIGH RESOLUTION IMAGING FROM FULL-WAVEFORM SONIC DATA

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(Schlumberger)

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ABSTRACT

Borehole Acoustic Reflection Survey (BARS) is an imaging technique that uses reflected acoustic energy at sonic frequencies to create images of the formation surrounding the borehole (e.g., Haldorsen, et al., 2005). The resolution of these images is 2-3 orders-of-magnitude higher than surface seismic and VSP images. The range is typically 10-20m.

The data are acquired by the Sonic Scanner™, a commercial sonic tool with 3 monopole transmitters and 104 receivers (13 receiver stations distributed along the axis of the tool, each with 8 individual receivers around the circumference of the tool). Using all monopole sources, the tool provides 312 waveforms at each depth position. The azimuthally separated receivers allow for the determination of the azimuth to a reflector.

Potential applications are assessment of well placement relative to formation topography, mapping reservoir structures, like sub-seismic beddings, faults, or fractures, and a guide for seismic interpretation.

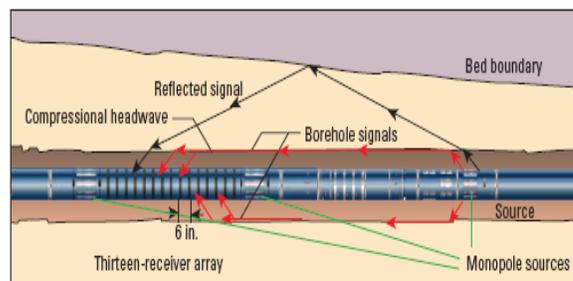
Data acquired for Hydro in the North Sea in a well deviated at 30-60° shows an interface dipping at 5°, clearly visible for at least 15m away from the wellbore (Haldorsen, et al., 2006). From the petrophysical logs at its intersection with the borehole, the event is identified as a 1m thick coal bed.

For the South Marlim field, the BARS image generated for Petrobras shows a turbidite reservoir varying in thickness from 4 to 10m over a 544m horizontal section of the well (Maja, et al., 2006). A flat horizon seen about 1m above the tip of the well may indicate the presence of segregated gas. The BARS image supplements information inferred from other geophysical logs. The agreement with the surface seismics is encouraging, despite the enormous difference in scale.

From the Middle East we have examples showing significant discrepancies between assumed and actual well placement.

INTRODUCTION

The objective of a Borehole Acoustic Reflection Survey (BARS) is to create a high-resolution image of the formation surrounding the borehole. The image is created by recording and processing acoustic energy reflected by inhomogeneities in the formation. The acoustic energy is generated and recorded by the Sonic Scanner™, a new generation tool built for sonic logging.



Sonic Scanner measurement.

Fig. 1 BARS geometry and concept. Energy generated by the acoustic source and propagating along the borehole is used for standard sonic logs. Some energy penetrate the formation and is reflected by inhomogeneities in the formation outside of the well bore.

The Sonic Scanner tool has 3 monopole transmitters and 13 receiver stations, each with 8 receivers at different azimuths around the perimeter of the tool, for a total of 104 receivers. Using all monopole sources, the tool provides 312 waveforms at each depth position. Figure 1 illustrates the concept of BARS using the Sonic Scanner. Energy generated by the acoustic source and propagating along the borehole is used for standard sonic logs. Some energy penetrate the formation and is reflected by inhomogeneities in the formation outside of the well bore. The section of an interface closest to the borehole will not be well imaged using long source-receiver offsets due to the large reflection angles involved. Large reflection angles means low resolution (see, e.g., Miller et al., 1987). For an object at a larger

distance from the borehole, one should expect to see little difference in resolution between images obtained from data generated by the individual monopole sources. The use of all three sources provides a larger range of offsets and better imaging conditions.

The BARS technique generates acoustic images at a resolution that is 2-3 orders of magnitude higher (and accordingly smaller range) compared to borehole seismic images. Potential applications for BARS are well placement relative to formation topography, reservoir structural analysis and characterization. High-resolution images around the well would also help identifying sub-seismic inter beds, faults or fractures. Provided in a timely way, the information provided by the BARS images could support decisions on well completion. In this paper we present three examples of using BARS images: one pilot study for Hydro in the North Sea, one example from the South Atlantic where Petrobras used BARS images to assist the understanding and description of a complex turbidite reservoir, and, lastly, one example from the Middle East where the BARS images were used to confirm (or not!) the placement of a well geosteered relative to a shale caprock.

PROCESSING

The processing for obtaining BARS images has three basic steps (Haldorsen, et al., 2005):

- 1) 2D adaptive prediction-error filter
- 2) Migration
- 3) Azimuthal focusing

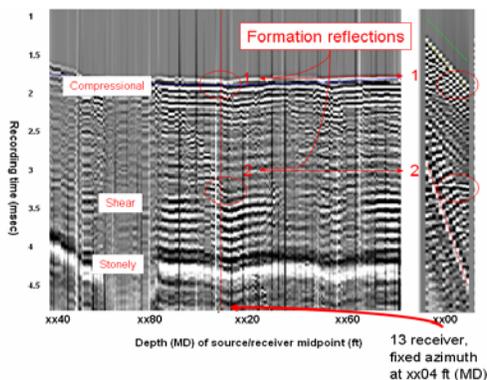


Fig. 2 Raw Far Monopole section with formation reflections.

In addition to the raw sonic waveforms, the well deviation and the sonic logs are required, as well as measurements of the orientation of the tool. Thanks to

recent software improvements, the full-waveform sonic data can be processed to a quick-look image within a few hours of the acquisition.

Figure 2 shows a small segment of raw data over a depth interval of about 140 ft (Haldorsen, et al., 2006). The main panel shows data generated by the Far Monopole transmitter and captured by a single receiver, at 0° azimuth and 15 ft offset from the transmitter. The display provides clear indications of direct compressional, shear and Stoneley energy. At offsets as long as 15 ft, these modes are separated and can easily be identified visually. The single-offset raw waveforms give very little indication of reflected energy as the primary compressional, shear and Stoneley are all of significant higher amplitude than any possible reflection. Also shown is common-source-point gather of waveforms recorded at a fixed azimuth using all 13 receiver at offsets from the source ranging from 11 to 17 ft. For this gather, the transmitter depth was xx04 ft. Again, the shot gather is dominated by the direct compressional shear and Stoneley waves. However, two events can be identified, showing abnormal time/offset move-out relationship. Of particular interest is the event arriving at the receivers at after between 3 and 3.5 ms.

2D adaptive prediction-error filter - To separate reflected energy from directly transmitted energy, we use a velocity filter based on an adaptive-interference-cancelling (AIC) filter explored by Meehan, et al., 1998. The AIC filter is applied to the common-shot gathers for each of the eight sets of receivers. The filtered data is found by minimizing the energy of the unpredicted wavefield.

Migration - The filtered data in are used as input to GRT migration (Miller et al., 1987), using the known geometry and smoothed velocities from the sonic slowness log. The (depth) migration is carried out on each set of azimuthal receivers separately and as a result gives 8 images, one for each set of azimuthal receivers. The migrated images are stacked to increase the signal to noise. Each migrated image is centered on the corresponding receiver group and the next step is to resolve the azimuths of possible reflections.

Azimuthal focusing - The individual images obtained from data captured by either of the eight sets of azimuthal receivers for a fixed tool receiver station essentially measures distances perpendicular to the borehole to any given reflector from eight different vantage points. This makes it possible to perform a formal triangulation to find the positions of the reflectors.

The diameter of the tool is effectively used as baseline for a formal triangulation. Although helped by adaptive filters (Haldorsen, et al., 2005, Meehan, et al., 1998), with a tool diameter of around 1/4 ft, one should expect limited resolution in azimuth, with somewhat better resolution for the higher-frequency components of the image (corresponding to > 10 kHz at formation velocities of 10000 ft/s). Reflectors that are not well resolved, or reflectors that are exceptionally strong, may generate ‘ghosts’ at the opposite side of the well bore. One may expect that a tool with a larger diameter would give less smearing. Similarly, increasing the transmitter frequency should improve the azimuthal focusing - however, at the cost of decreasing the range of the image. Furthermore, using the Far Monopole transmitter, one should expect to have lower dominant frequency for the image of a near-borehole reflector than for a reflector far from the borehole, leading to poorer azimuthal focusing for near-borehole reflectors.

INTERPRETATION

To interpret BARS images one needs to look at them in conjunction with other available geological and geophysical information, such as Surface Seismic, Borehole Seismic images and petrophysical and geological logs.

NORTH SEA EXAMPLE

Sonic waveform data were acquired for Hydro in an exploration well in the Brent formation in the Norwegian sector of the North Sea. With well deviation up to 60°, the tool was conveyed on drill pipe using a Tough Logging Condition (TLC) technique.

The BARS data were acquired in a single run along with dipole shear data, therefore not requiring an additional logging run for BARS. However, working from a floating rig during a long period of very bad weather in the North Sea, Hydro limited the BARS acquisition to a smaller section of the well, acquired during a short time window with a little calmer weather.

The three monopole sources were fired sequentially. For each shot, 312 waveforms were recorded, each consisting of 1024 samples. Simultaneous with this, shear-dipole data were recorded using chirp drives, resulting in very high data rates, limiting the logging speed to 450 ft/hour.

The image quality was affected by the difficulty with accurately controlling the tool depth. The problem of knowing the depth of the tool is related to the TLC

operation from a floating rig (semi-submersible) subject to heavy sea swell. While the platform is moved vertically by the sea swell, the drill pipe is kept dynamically at rest. However, as the platform moves, the length of the wireline supporting the sonic tool changes. The acceleration of the tool is measured downhole, and the tool depth subsequently corrected for variation in the speed of the tool. However, the “speed correction” cannot correct for the gross depth errors like the errors caused by sea swell. For this reason, in a situation with significant swell, the waveform data may not be adequate for acoustic imaging of formation structures having an appreciable dip angle relative to the borehole. For imaging structures that are near-parallel to the borehole, errors in the tool depth are not as serious.

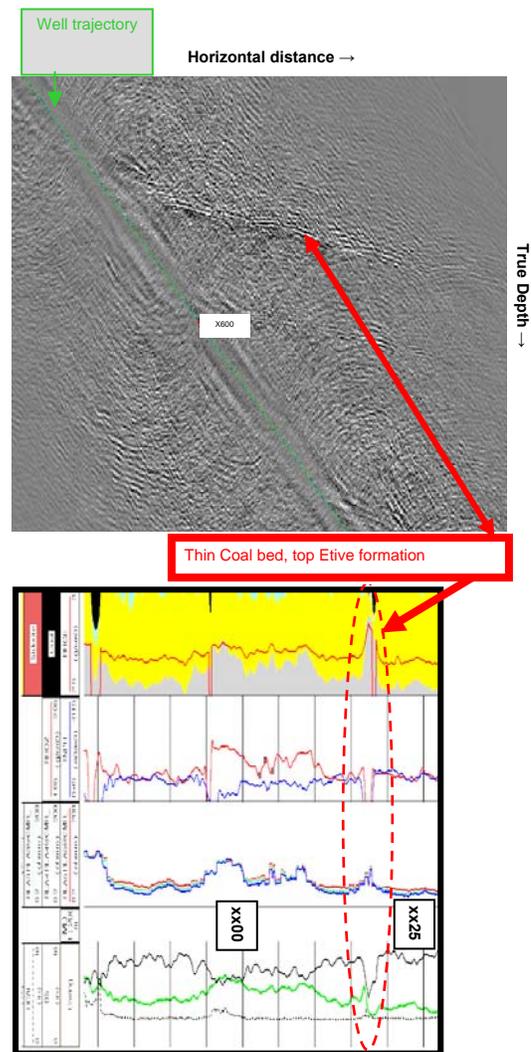


Fig. 3 North Sea example. On the top, the BARS image showing the Top Eive formation, identified from the logs displayed in the bottom part of the figure.

Figure 3 shows the final image in a true vertical section through the borehole. A strong event is clearly visible at a dip calculated to be 5°. This event has been identified from the petrophysical logs as the top Etive formation, representing a 1-m thin coal layer.

SOUTH-AMERICAN EXAMPLE

The South Marlim oil field, discovered in 1987 offshore Campos Basin, Brazil, saw in the 1990's some deepwater production records being established and the development plans for the field should allow reaching a peak production of 420,000 boe/d in 2010. South Marlim is a turbidite reservoir of Upper Oligocene-Lower Miocene age. These reservoirs were initially thought to be homogeneous, widespread turbidite fans, but more recent studies based on later well data and 3D seismic surveys found that they can be rather complex and heterogeneous (Bruhn, 2001).

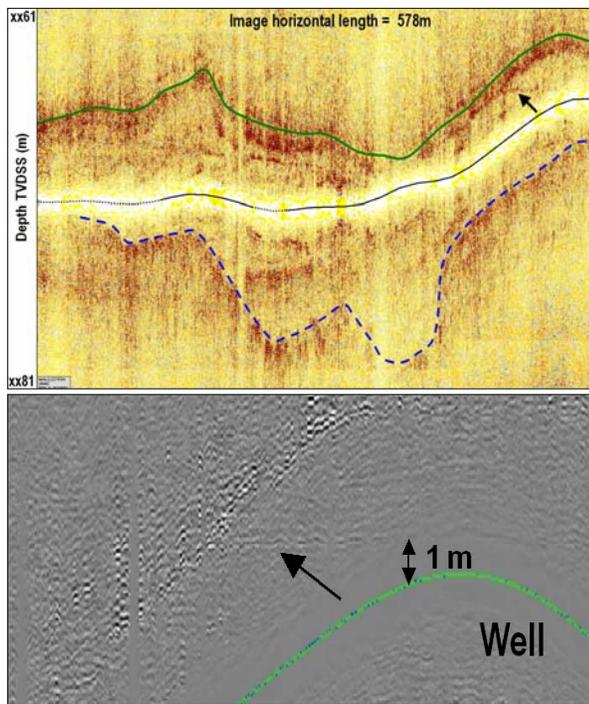


Fig. 4 The top and base of the main turbidite sand are interpreted in the BARS image on the upper panel. The lower panel gives a close-up near the tip of the well. The arrow on the flat spot indicates a possible oil-gas contact mapped over almost 100m by all 3 monopole transmitters.

In order to better define the turbidite reservoir geometry at one South Marlim's horizontal producer location, Petrobras decided to run a Borehole Acoustic Reflection Survey (BARS), the first time ever this was attempted in this type of environment. The sonic tool

was drill-pipe conveyed (TLC) in order to collect the data. The processed images have a depth of investigation of 10 m and a vertical resolution of 0.3 m.

The BARS technique mapped the main turbidite sand over 544m of horizontal well section (Figure 4), showing thickness variations between 4 and 10m (Maia, et al., 2006). No other measurement provided this level of information. At the pilot-hole, the sand was 4 meter thick and the horizontal well was geosteered assuming constant sand thickness. A flat spot event was mapped one meter above the tip of the well, suggesting segregated gas in that reservoir area, which lies on a structural high. The well produced limited amounts of gas supporting the direct gas-oil contact indicator from the acoustic method. This is possibly the first fluid contact mapped by deep sonic imaging technique. The BARS images were consistent with the dips estimated from image logs, with the geosteering data and to a great extent, with the pilot-hole results. Their correlation with surface seismic is encouraging, despite the enormous difference in scale.

Petrobras plans to use the high-resolution sonic images in order to provide lateral constraints to seismic acoustic impedance inversion and as an input to geological modeling. The resulting improvements in the static model should in turn enhance considerably the prediction capability of the reservoir dynamics simulators.

MIDDLE-EAST EXAMPLE

The BARS imaging was run over about 6000 ft in this well to confirm the placement of the well below the shale caprock of the reservoir. The well had been geosteered using an omnidirectional resistivity tool with the objective of staying within 1 to 5 ft from the caprock. The shale caprock, identified from gamma-ray logs, was intersected near the top end of the logged portion of the well. After that, the BARS image shows the well as heading down, away from the caprock which disappears outside the range of the image to reappear again and stay near the upper range of the image until it finally disappears near the end of the imaged well section. The vertical extent of the image was only ±7m from the well bore. The reason for this limitation was that it was argued before the survey that if you only needed to see 5 ft you would not need to record more than 2.5 ms of waveforms. Next time, more data will be recorded.

The caprock was again intersected by the well about 500 m beyond the deepest data recorded by the Sonic Scanner, having quite possibly left 7 m thick play over

about 1.6 km. After about 3 month the well was producing more than 50% water. The client company is considering drilling their options for getting back into the reservoir.

CONCLUSIONS

Allowing full-waveform sonic imaging, the Sonic Scanner adds a new and versatile tool for the operators to explore. Providing image resolution several order of magnitude higher than what is available from seismic data, and with relatively rapid processing turnaround, sonic images may help resolve reservoir and completion questions, improve decision quality and reduce risk. Current experience has demonstrated the tool's ability to provide data that can be used to image interfaces as far as 100 ft (30 m) from the borehole. With further improvements in the processing algorithms, one may expect this range limit to be extended.

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Jakob B.U. Haldorsen, a Scientific Advisor with Schlumberger-Doll Research (SDR) in Cambridge, MA (USA), received a Cand. Mag. degree in 1967 and a Cand. Real. degree in physics from the University of Oslo in Norway in 1971 and spent six years in research and teaching at the University of Oslo and at the European Organization for Nuclear Research in Geneva, Switzerland. After joining Geco in Oslo in 1981, he worked in several positions, including R&E manager in Houston. After Geco became part of Schlumberger in 1987, he was transferred to Schlumberger-Doll Research in Ridgefield, CT, as a Member of the Geoacoustics department, to Schlumberger Cambridge Research in England, in 1992 to Geco-Prakla in Hannover, Germany, and finally returned to SDR in 1995. Jakob has worked on algorithmic and physics problems related to imaging using data acquired in high-noise environments.

Badarinadh Vissapragada, a Petrophysics Advisor and Domain Champion with Schlumberger Offshore in Stavanger, Norway, obtained an MS degree in geophysics, and an MS technology degree from Andhra University, Waltair, Andhra Pradesh, India. After completing postgraduate studies in geophysics, he began his career in 1982 with the Oil & Natural Gas Corporation (ONGC). He worked for 13 years for ONGC at Mumbai onshore, Assam (Nazira) and in the western region (Baroda). In 1995 he joined the Oil and Gas division of Reliance Industries of India at Mumbai and worked two years in the Reliance-Enron joint-venture project, in the Panna-Mukta and Tapti oil fields. Since joining Schlumberger in 1997, as a senior petrophysicist in Abu Dhabi, UAE, he completed many field-wide petrophysical studies. He has been in Stavanger, Norway since 2002.

William H. Borland, a Principal Geophysicist with Schlumberger Gulf Area in Abu Dhabi, UAE, received his BS degree in geophysical engineering in 1973 from the Colorado School of Mines, Golden, USA. After graduation he joined Schlumberger and had various assignments throughout Australia and the Far East. From 1982 to 1984, he also taught undergraduate borehole geophysics at the West Australian Institute of Technology in Perth. From 1985 to 1987, he worked on new sensor technology at the Schlumberger Engineering Center in Fuchinobe, Japan. He spent the next two years at the Schlumberger Europe Unit in London and also helped developing interactive workstations. In 1990 he transferred to Kuala Lumpur, to Bangkok, Thailand in 1992, 1999 to Jakarta, Indonesia. He has been in Abu Dhabi, UAE since 2002.