Progress and Issues in Single Well Seismic Imaging

**Thomas M. Daley, Ernest L. Majer, and Roland Gritto*
Lawrence Berkeley National Laboratory

Jerry M. Harris
Stanford University

Summary

Over the last five years as part of DOE's Fossil Energy Program, Lawrence Berkeley National Laboratory (LBNL), in conjunction with industry, has been developing and applying methods of extending the penetration of conventional seismic logging from a few meters out to tens if not hundreds of meters. The use of borehole seismic sources and sensor strings, capable of exciting frequencies from 10s to 1000s of Hz, on a single cable is termed single well seismic imaging (SWSI). The SWSI acquisition work within our project has progressed through various field tests to a current system capable of CMP type borehole surveys with multiple borehole source and receiver options. Recent field experiments have been aimed at salt dome imaging from wells within and outside of a salt dome.

Introduction

Borehole CMP imaging is accomplished by increasing the distance between the source and the receiver in the well from a few meters to over a hundred meters, depending upon the desired distance of investigation. However, as one increases the source receiver distance many problems not encountered in conventional well logging become more severe. In effect, one now is trying to image in a true 3-D sense away from the well, therefore, directionality becomes important for the transmitted as well as the received signals, particularly when multicomponent sources and/or receivers are used. Although this can be an advantage, such issues as source generated noise, radiation pattern, tube waves and other sources of noise become more apparent. To address these, as well as other issues, we have been carrying out a series of experiments on a variety of scales and conditions to identify fundamental issues and solutions to advance the practice of single-well imaging.

The distances between source and receiver have ranged from a few meters to over 150 meters. The sources used have been piezoelectric sources with frequencies between 1 kilohertz to 10 kilohertz and mechanical orbital vibrator sources with frequencies between 50 Hertz and 400 Hertz. In most cases the objective has been to perform CMP imaging from the borehole by using multiple receivers deployed below the source. Both hydrophones and three component locking geophones have been used. The target of most investigations has been vertical or near vertical features at distance from the borehole. To date the targets have been permeable fractures, but it is also possible to image geologic/stratigraphic boundaries, edges of faults and other structures (such as salt domes), or any other feature which will cause a reflection back to the borehole.

Method

LBNL's development of SWSI acquisition technology has progressed from initial surveys using multiple cables in shallow wells to a robust, oil field scale, single cable system capable of utilizing various sources and sensors. The field testing of SWSI systems is shown in Table 1. Our first application in 1994 used a piezoelectric source and hydrophone receivers on separate cables to collect CMP data in a fractured limestone aquifer. The data successfully imaged a hydrologically significant fracture with a constant velocity CMP section (Majer, et. al., 1997). Testing with a single cable in a deep well (over 1.5 km) at the MIT test site in Northern Michigan successfully acquired data in the Antrim shale section and the Niagran reef section (Daley, 1997). This test showed that borehole sources and sensors, such as those routinely used for crosswell surveys, could be operated on a single cable, in a single borehole, and acquire CMP type shot gathers.

Examples

The initial testing under the DOE project was performed at a salt dome where an oil industry consortium (Salt Imaging Consortium, SIC) was conducting experiments in salt dome imaging. Cooperation between SIC and the SWSI project led to a series of field tests at a salt dome site. The initial testing using equipment developed by CONOCO research and donated to LBNL was performed in Nov. 1997 in a well outside the salt dome (Daley, 1998). The replacement borehole digitizer system used a fiber optic (FO) transmission system developed in 1998 by OYO Geospace Instruments, and updated in 1999.

Table 1. LBNL SWSI Field Acquisition

Year	Site	Comments
1994	**Conoco Newkirk Test Site**	**Shallow Well With Multiple Cables**
1996	**MIT Michigan Test Site**	**Deep Well POV Source**
1997	**Salt Dome**	**Multiple Sources and Sensors**
1998	**Texaco Humble Test Site**	**Fiber Optic telemetry - Orbital Vibrator**
1998	**Salt Dome**	**Fiber Optic telemetry**
1999	**Baker Atlas Test Site**	**Fiber Optic telemetry - O.V. and P.O.V. source**
1999	**Salt Dome**	**Improved Fiber Optic / Multiple Sources and Sensors**

Initial testing of the FO SWSI system took place in Nov 1998 at Texaco's borehole test site in Humble, Texas. This testing used an orbital vibrator and a 5 level 3-component wall-locking accelerometer sensor string. Data was acquired at depth between 664 ft. to 1000 ft at 8 ft intervals. The source-receiver offsets were 57 to 89 ft. Multiple seismic arrivals were observed. With SWSI data successfully collected using the FO acquisition system at the Humble test site, a more complete survey was planned for a well inside the salt dome. Acquiring data within the salt dome would allow data analysis using a constant velocity medium, as well as reducing interbed reflections. With our 16 channel recording system, and 5 level 3-component sensor string, we hoped to acquire 3 fans with different offset giving increased CMP fold. The 3-component recordings could be "rotated" in processing to increase the signal-to-noise ratio of reflections. The inherent problem of tube-wave energy was addressed by increasing the source receiver offset from previous surveys up to 231 ft. (thereby increasing the usable time window before the tube wave arrival). Field acquisition problems limited the data acquisition and only two fans were acquired with the orbital vibrator source over the depth range 3380 ft. to 4380 ft.

The data were processed into common receiver gathers, including deconvolution and decomposition of the orbital vibrator source signal (Daley and Cox, 1999). Figure 1 shows the horizontal components for one receiver gather. The tube wave arrives at about 35 ms and dominates the later data by reverberations. These data have been bandpassed 150 - 330 Hz, and enhanced using a Wiener Levinson prediction filter 5 samples (2.5 ms) and 10 traces long.

The vertically propagating S-wave is visible on the horizontal components between 15 and 30 ms, depending on source-receiver offset. Polarization of the S-wave is observable by comparing the horizontal components for each source. In a homogeneous medium, the orbital vibrator will generate a pair of orthogonal, linearly-polarized, horizontally propagating SH-mode shear waves, which fits our observations. Changes in S-wave velocity as a function of depth are observable. The changes in travel time correspond to velocity changes from sediment to salt (about 6000 ft/s and 8000 ft/s, respectively). Also notable is the disruption of coherent arrivals between about 3600 ft. and 4100 ft. We believe the coupling of the borehole to the surrounding medium (salt or sediment) is responsible for the dramatic changes in direct arrival coherency (and, by implication, reflection arrival coherency).

Also observable in the common receiver gathers are various reflected phases. Figure 1 (top right, and bottom left panels) shows an S-wave reflections from the change in velocity seen at 4260 ft. (source elevation). The apparent velocity is twice the actual velocity for a reflection from an interface below or above both source and receiver. Also observed are body-wave to tube-wave conversions. These results were encouraging, although we were not able to acquire enough data in zones of good arrivals to generate CMP type imaging. Additionally, we felt the time window before tube wave arrivals needed to be increased by using larger source-receiver offsets. An important finding from this data set was that the fiber optic wireline did allow real-time multi-channel data acquisition.

During 1999, the FO acquisition system was upgraded to one using two FO wires (one for data transmittal uphole and one for command transmittal downhole) and to improve electrical isolation of the borehole digitizer. The borehole digitizer sample rate was extended, giving usable seismic response to 3800 Hz. This extended bandwidth allows much improved recording of piezoelectric sources, and is essential to take full advantage of the relatively high values of Q (low attenuation) observed in subsurface units.

With this system, in Oct 1999, we were able to acquire CMP SWSI data in a well from 4600 ft to 1300 ft with source-receiver combinations including orbital vibrator and piezoelectric sources with 3-component geophone, and hydrophone sensors. High frequency (1 -3 kHz) P- and S-waves are generated by the piezoelectric source and are observed with geophones and hydrophones. Significant tube-wave velocity variations are observed. P- and S-wave reflections from salt/sediment interfaces are observed, as are mode converted tube-wave reflections. The initial CMP analysis indicates a lack of coherent reflections from an assumed near-vertical salt dome flank. We believe the weak reflections are due to poor source coupling from the borehole to the formation. Presented with this paper will be the results of recent surveys and recommendations of use.

Conclusions

To date it appears that single-well seismic imaging could be a powerful method, especially if used in a time lapse sense and where high resolution is needed and well spacing is such that crosswell cannot be used. Recent and near future advances in instrumentation will make the method more economical and possibly deployable through the end of tubing. Obvious applications are hydrofracture monitoring, steam/water flooding monitoring, fracture mapping and validation of drilling paths in horizontal drilling applications.

References

Daley, T.M. and Cox, D., Orbital vibrator seismic source for simultaneous P- and S-wave crosswell acquisition, Lawrence Berkeley National Laboratory Report LBNL-43070, Berkeley, CA, March 31, 1999, Geophysics (submitted May 1999).

Daley, T.M., Single Well Seismic Imaging Tests: Nov 1997 at Bayou Choctaw Site, LBNL Report #42672, Lawrence Berkeley National Laboratory, Berkeley CA, February 1998.

Daley, T.M., Single Well Seismic Imaging in a Deep Borehole using a Piezoelectric Orbital Vibrator, LBNL Report #42673, Lawrence Berkeley National Laboratory, Berkeley CA, June 1997.

Majer, E.L., Peterson, J.E., Daley, T.M., Kaelin, B., Queen, J., D'Onfro, P., and Rizer. W, Fracture Detection using Crosswell and Single Well Surveys, Geophysics, v62, n2, 1997.

Acknowledgements

This work was supported by the Assistant Secretary for Fossil Energy, National Petroleum Office of the U.S. Department of Energy and Federal Energy Technology Center Low Permeable Natural Gas Program under Contract No. DE-AC03-76SF00098.

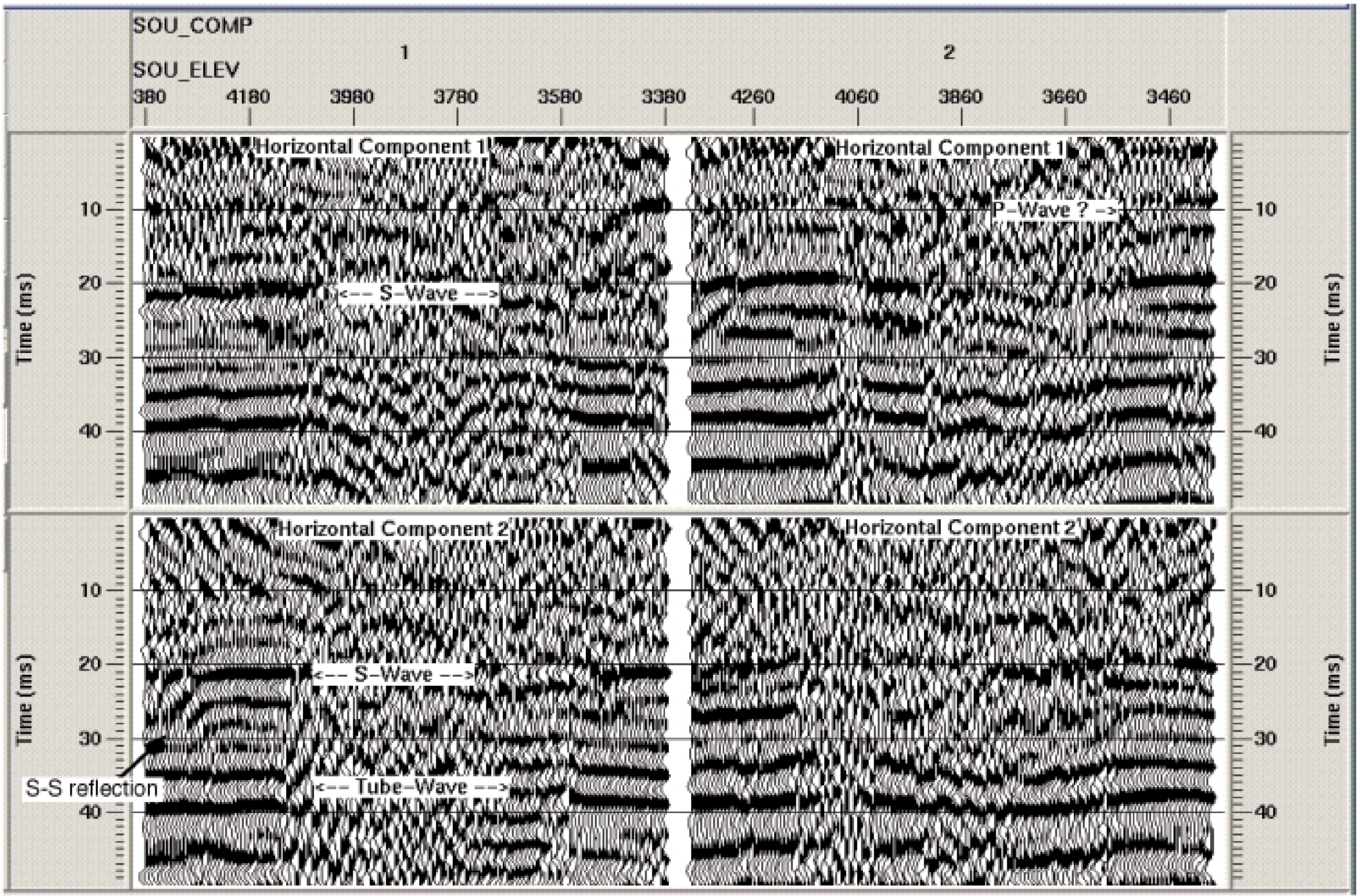

Figure 1. Single well seismic data from the bayou choctaw salt dome, well #28. The source was above the receiver string. T he four panels are a common offset sort (source-receiver offset =176 ft). Source depths (SOU_ELEV) are in feet. The source was an orbital vibrator with two orthogonal horizontal source components(left and right panels). The sensors were 3-component with the horizontals shown here in the top and bottom panels. Direct S-waves and reflected S-waves are observed. The depth range 3600 ft to about 4100 feet has interbedded salt and sediments and less coherency of seismic arrivals.