Borehole Seismic Monitoring of Seismic Stimulation at Occidental Permian Ltd's – South Wasson Clear Fork Unit

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Introduction:
Seismic stimulation is a proposed enhanced oil recovery (EOR) technique which uses seismic energy to increase oil production. As part of an integrated research effort (theory, lab and field studies), LBNL has been measuring the seismic amplitude of various stimulation sources in various oil fields (Majer, et al, 2006, Roberts, et al, 2001, Daley et al, 1999). The amplitude of the seismic waves generated by a stimulation source is an important parameter for increased oil mobility in both theoretical models and laboratory core studies. The seismic amplitude, typically in units of seismic strain, can be measured in-situ by use of a borehole seismometer (geophone). Measuring the distribution of amplitudes within a reservoir could allow improved design of stimulation source deployment. In March, 2007, we provided in-field monitoring of two stimulation sources operating in Occidental (Oxy) Permian Ltd's South Wasson Clear Fork (SWCU) unit, located near Denver City, Tx. The stimulation source is a downhole fluid pulsation device developed by Applied Seismic Research Corp. (ASR). Our monitoring used a borehole wall-locking 3-component geophone operating in two nearby wells.

Source Description:
The ASR source is located at depth in a well, driven by a surface pump jack which lifts and compresses a column of wellbore fluid with 3000 - 4000 psi pressure and then releases the column to fall and generate a pulse (presumably consisting of fluid pressure and elastic body waves as well as borehole guided waves) which is transferred to the reservoir formation through elastic wave propagation and/or fluid pressure propagation. Fluid pressure propagation assumes fluid connection to a reservoir via perforations in the casing. However, the source can be operated with or without perforated casing.

Data Acquisition:
An ASR source was located in wells 8510 and 7535, at depths of 5679 ft (1731 m) and 5060 ft (1542 m), respectively. Monitor wells used were 7545 and 7546. The well head to well head distances are as follows:
7535 - 7545: 624 ft (190 m)
7535 - 7546: 2608 ft (795 m)
8510 - 7546: 4062 ft (1238 m)
8510 - 7545: 4834 ft (1473 m)

Monitoring was accomplished by using a surface geophone at the source. The signal from the surface geophone was recorded and was used as a 'zero time' trigger signal for the recording system. Previous monitoring of the ASR source has shown that the surface response is quite repeatable and this was true for both wells monitored here. The time for the seismic energy to reach the surface is unknown (as is the exact nature of the waves propagating to the surface), so a one or two second pre-trigger recording time was used. Previous monitoring at an AERA site (Daley, et al, 2003) did indicate the source pulse is transmitted up the steel sucker rod (the velocity of steel is about 18,000 ft/s). Other acquisition details at the Oxy SWCU site are as follows:

Recording System: Geometrics GEODE (24 bit, sigma-delta sampling)
Recording Format: SEG-2
Sample Rate: 0.25 ms
Anti-alias filter: 1700 Hz high cut
Record Length: 4 s
Pre Trigger Recording: 1 or 2 s
Sensor: Wall-locking 3-component geophone
Geophone: Geospace SMC-1850 14 Hz
Channel 1: Horizontal
Channel 2: Horizontal
Channel 3: Vertical
Channel 4: Surface Geophone I/O PE-3 about 3 m from source well head.
Depths recorded: 4200-7400 ft at 200 ft intervals

Data Processing:
The following processing flow was used for each of the 4 data sets:

1) Input SEG-2 file
2) Pick 'zero time' from first peak of source monitor (2 passes of picking)
3) Align all files with zero-time at 1000 ms
4) Edit noisy records
5) Stack files for each source for each sensor depth (about 40-80 files)
6) Bandpass filter data 8 – 20 Hz (data peak at about 15 Hz)
7) Compute rms and peak amplitude in a time window around arriving energy. Time window of 1400-1800 ms for 7535-7545 and 7546-7535, 2000-2800 ms for 8510-7546.
8) Calculate strain from peak amplitude (peak velocity)

Data Results:
The processed data are shown in Figures 1-4 for each of the 4 well pairs. The 3 geophone components along with the stacked surface monitor data are shown. Compressional P-wave energy (identified by apparent velocity of > 20,000 ft/s – appropriate for carbonates) is observed in 3 of the well pairs, all except the longest distance 8510-7545. For the well pair 7546-8510 (Figure 4) some coherent energy is seen at about 1600-1800 ms, before the labeled P-wave, however we felt this signal was to low in S/N for identification and analysis. An event with no apparent moveout is seen at about 1100 ms on all the borehole geophone data. We interpret this to be some type of

electrical crosstalk from the high amplitude surface signal. This interpretation is based on the lack of moveout. The presence of some electrical crosstalk is indicative of the very low signal levels observed. The overall noise level of the observation boreholes was quite low (< 0.01 mV output from the borehole geophone compared to 100 mV from the surface geophone). Individual recordings of the source did not have observable signal. Only with stacking of 40-80 source repetitions and narrow bandpass filtering was the data in Figures 1-4 observable. The spectral content of the data is peaked at about 15 Hz, as shown in Figure 5.

The event interpreted as a P-wave was analyzed for peak strain amplitude. The output of each geophone component was converted to voltage using the analog-to-digital calibration of the recording system (1 mV/count) and then to particle velocity using the geophone specification (0.7 V/in/s). The particle velocity, v, was converted to peak-to-peak displacement, d, using a frequency, f, of 15 Hz (Wilcoxon Research).

$$d = 0.3183 * v / f$$

The displacement is converted to strain, s, using frequency and P-wave velocity, α, of 6000 m/s (Aki and Richards).

$$s = 2\pi f d/\alpha$$

The peak strain for each of 4 well pairs is shown in Figures 6a and 6b. The strain levels are approximately 10^{-10} , this is a very small strain, as indicated by the low signal levels. Note that the strain level measured in well 7545 from the source in 8510 (Figure 6b, left) is not observable signal (it is noise). The background noise strain, measured with no source operating, and no stacking, is shown in Figure 7 with values of 10^{-9} to 10^{-10}, again demonstrating that the noise is larger than the signal for a single source pulse.

Interpretation/Conclusions:
The ASR source is able to propagate energy over the fairly large interwell distances used in this study. Seismic energy generated by the ASR source in well 7535 was observed in well 7545 (624 ft offset) and well 7546 (2608 ft offset). Energy from the source in well 8510 was observed in well 7546 (4062 ft offset), but not in well 7545 (4834 ft offset) where the signal-to-noise ratio was below 1 after stacking. The observed seismic energy has about 15 Hz dominant frequency and strain levels of 10^{-10}. It is interesting that the energy observable with 40-80 stacks of the source is not propagating directly, but appears to be coming from above the source. Two possible options are that the surface pump jack is acting as a secondary source, or that a low velocity layer is acting as a wave guide. The wave guide would allow energy to travel farther and would scatter P-waves downward (and probably upward) when it reached discontinuities such as boreholes. A low velocity layer between 3400 and 3800 ft (observed in sonic log data) is a potential wave guide. The directly propagating energy must have lower amplitudes than those observed here and would require greater stacking to observe. Because the observed seismic energy is not 'direct' (ie approximately straight ray), interpreting relative amplitudes is difficult. Forward modeling of wave propagation, such as finite-difference

modeling, would be useful to investigate potential wave paths and to understand the distribution of seismic energy within the reservoir.

References:

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Wilcoxon Research, vibration calculator, slide-chart, 1977.

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Figure 1: Stacked Data
Monitor Well 7545 Source Well 7535

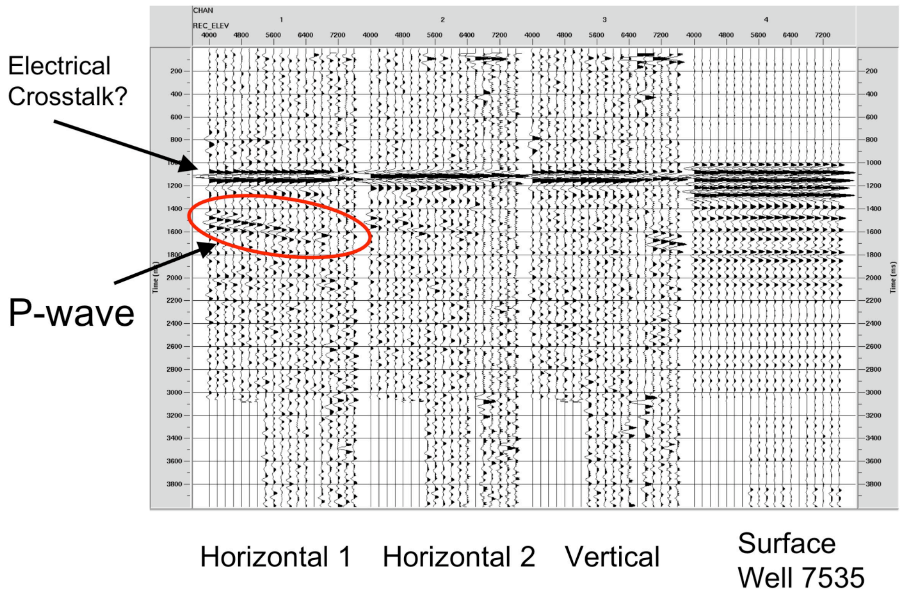


Figure 2: Stacked Data
Monitor Well 7546 Source Well 7535

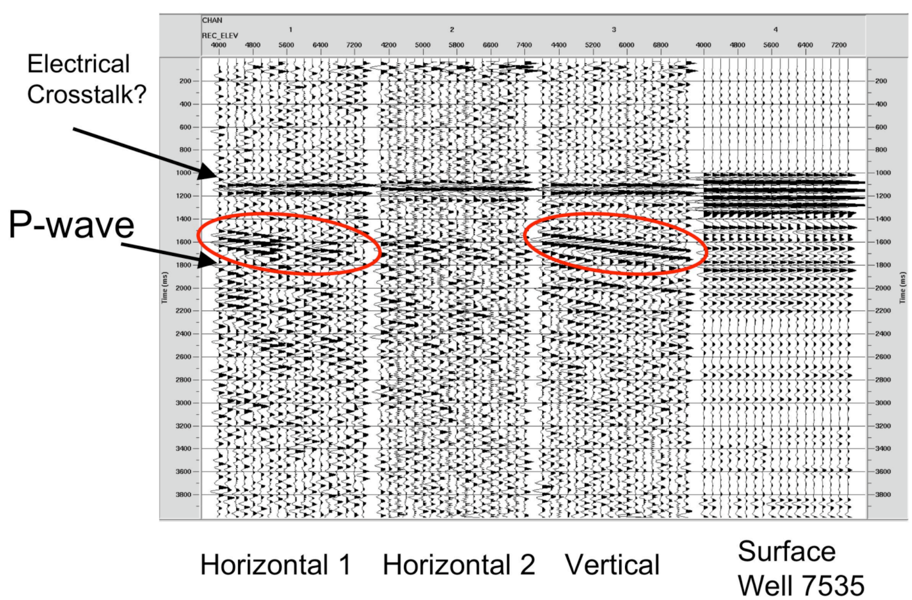


Figure 3: Stacked Data
Monitor Well 7545 Source Well 8510

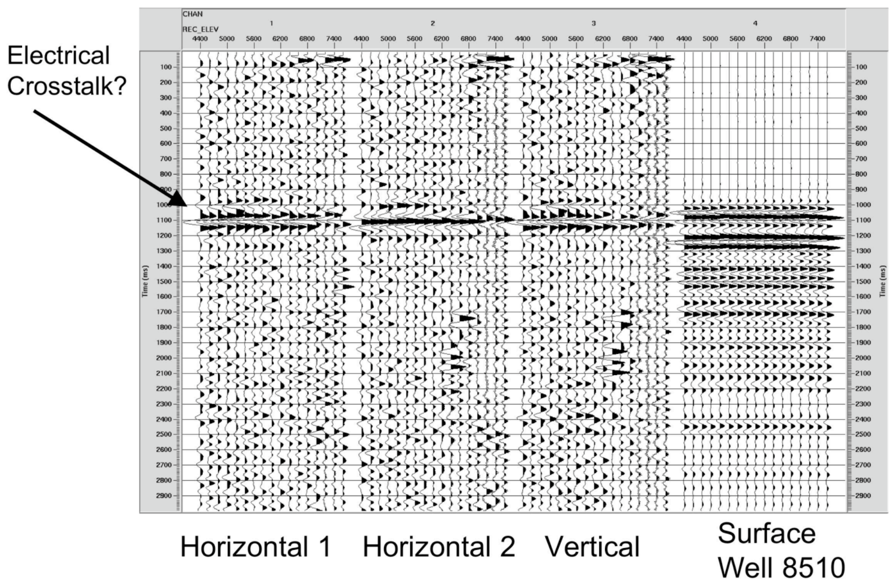


Figure 4: Stacked Data
Monitor Well 7546 Source Well 8510

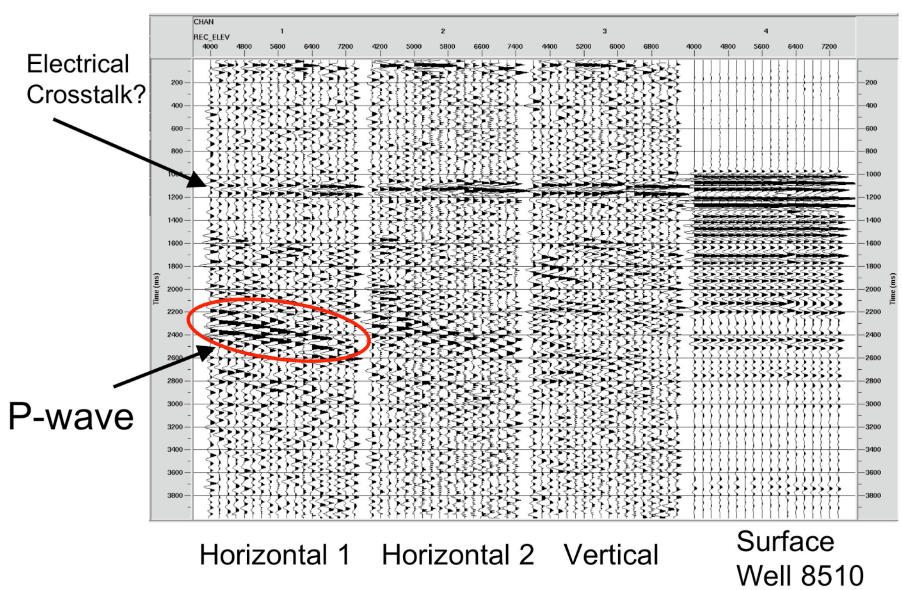


Figure 5: Spectral Analysis
Vertical Component with 50 Hz High Cut
Source 7535 Monitor 7546

Peak Amplitude at ~15 hz

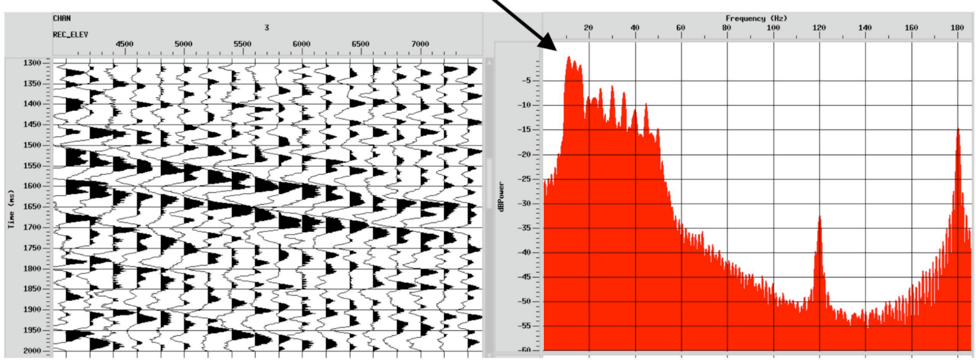


Figure 6a: Strain Amplitudes for 2 Well Pairs
3 Channels per Depth

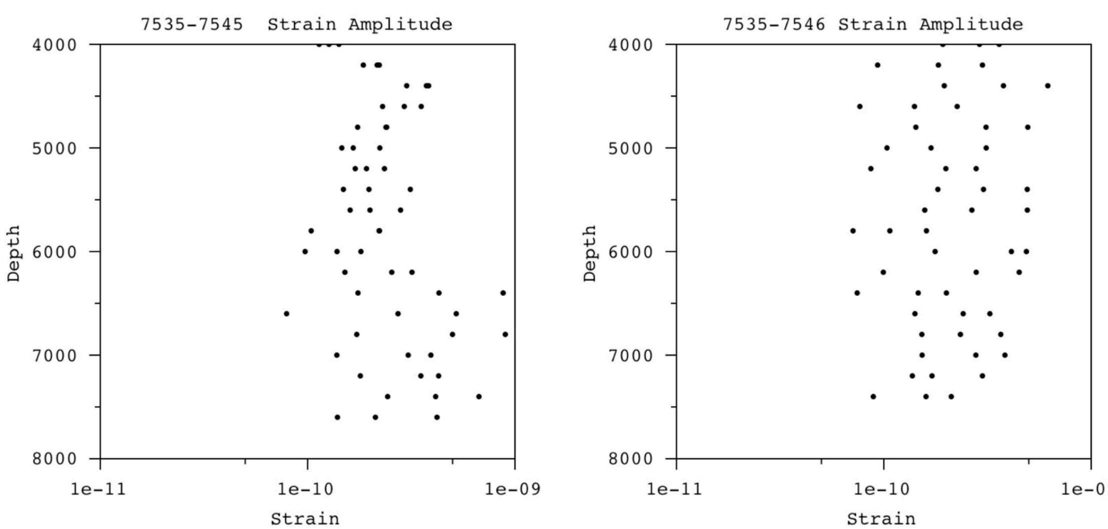
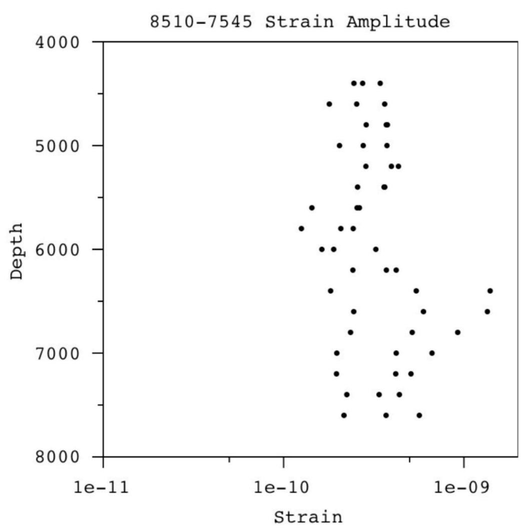


Figure 6b: Strain Amplitudes for 2 Well Pairs
3 Channels per Depth



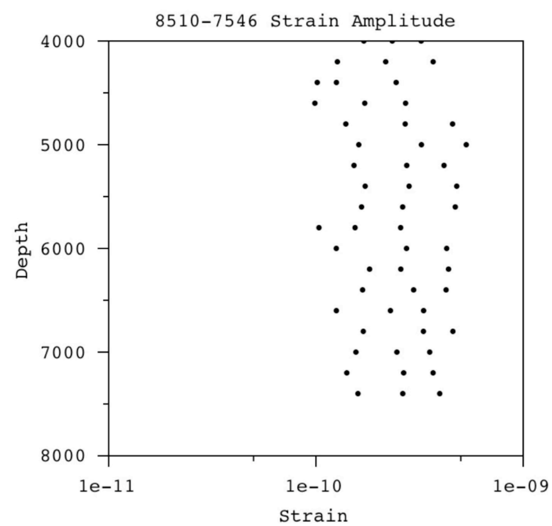


Figure 7: Strain Amplitude of Background Noise
Well 7546