Progress Report
DE-FC26-04NT15508
“Crosswell Seismic Amplitude-Versus-Offset for Detailed Imaging of Facies and Fluid Distribution within Carbonate Oil Reservoirs”

Principal Investigator: Wayne D. Pennington
Michigan Technological University
Date of Report: October 2005
Period Covered by Report: 01 October 2004 – 30 September 2005

Report authors:
Wayne D. Pennington, Roger M. Turpening, Sean P. Trisch, and Josh Richardson

EXECUTIVE SUMMARY:

The project is on schedule and on budget. The first dataset was successfully collected during the summer of 2005, and initial processing for crosswell imaging has been completed. Work is underway to interpret the amplitude-versus-offset (AVO) or, more precisely, amplitude-versus-angle (AVA) characteristics of the data in terms of lithology and fluid content.

A crosswell seismic survey was conducted at a dedicated test site that accomplished two tasks: (1) it imaged the carbonate reservoir (a Niagaran reef) between two monitor boreholes in crisp detail; and (2) it provided as wide a range as possible of angles of incidence for reflections of seismic waves from within the reef and at the reef’s upper surface. The stacked image obtained is extremely high quality, and the prestack data will be used to examine and demonstrate the usefulness of such data for determination of lithology, fluid content, and pressure for compartments within the producing field.

The survey was designed to collect transmitted waves in order to obtain a detailed velocity field through transmission tomography, and to collect reflected waves for high-resolution imaging and AVA studies. This required a thoughtful approach to the mechanics of data collection, in order to complete the survey in a timely manner.

The survey consisted of two parts. The first part, conducted over 3.5 days, was a detailed “conventional” crosswell survey, in which sources and receivers were located in positions designed to provide the crosswell transmission tomographic velocity model and the reflection data. The second part, conducted over one half-day, consisted of a suite of data, with 10-foot spacing, in which the receivers and sources were at equal depths for all shots, and extended to the shallowest depths of the boreholes below the till. This second experiment was designed to provide data for AVA studies at any interface, including those above or below the reef, and to ensure that the widest possible range of angles was obtained for all AVA studies.
The acquisition equipment consisted of a single seismic source and a set of ten (10) hydrophones in a string, spaced at 10-ft intervals. The source was activated repeatedly while moving uphole on wireline. The source signal consisted of a sweep of frequencies, up to 3000 Hz. This sweep was repeated 8 times for each “source point” and stacked. The signals received at most receiver stations showed that 3000 Hz data was easily obtained at the spacing of these boreholes (about 2000 ft).

Conventional Amplitude-Versus-Offset studies, conducted from surface seismic data, usually extend from an angle of incidence of 0° to about 30°. Special “wide-angle” or “far-offset” studies may extend to 40° or 45° at the most. Crosswell AVA starts at about 30° and extends to 90° at the limit. This produces effects that are not experienced in conventional AVO studies, including phase rotation, radiation pattern concerns, and even phase reversal. In addition, the reflections can be observed in two directions from the same interface – from above, and from below. This is not possible in conventional AVO studies, and will provide us with an extra degree of robustness in the crosswell environment. It will also provide us with an extra degree of quality control that is completely absent from conventional AVO studies.

The image obtained from the crosswell survey is excellent, and shows the interior of the reef at a resolution that has not previously been practical. At this time, the interpretation of these details is not complete, but we are moving forward with the AVA analysis in parallel with interpretation of the seismic image.

The crosswell seismic data set contained an unusual form of tube-wave noise. This noise is easily removed, but is worthy of study in its own right – it appears to have been caused by electromagnetic propagation of the source pulse through the earth and conversion to seismic energy at or near the receiver well. Analysis of this possible electroseismic signal is ongoing and no conclusions should be drawn at this time.
RESULTS OF WORK DURING REPORTING PERIOD:

Project Goal:
Our goal is to provide a methodology that will allow operators of oil reservoirs in carbonate reefs to better image the interior structure of those reservoirs and to identify those areas which contain the most oil remaining after initial production.

Approach:
We collected crosswell seismic data within a carbonate reef in Michigan to study the internal lithologic framework and fluid-phase distribution from the variation of seismic amplitude with angle of incidence. The challenge this approach faces is the strong dependence that both amplitude and phase have on the wide angles used in the crosswell environment. The benefits are derived from the extremely high resolution possible and the potential to image subtle variations using those very wide angles.

\[\text{Figure 1: Main survey geometry using a 10-foot source and receiver spacing. The reef is the non-horizontal body shown at about 4500 ft depth. Only transmitted rays are shown; reflected rays are not shown for clarity of visualization. Scale is 1:1}\]
A detailed survey was conducted in late June and early July at the dedicated test site we use in Michigan. Figure 2 shows a schematic cross section of that site based on pre-existing information.

Figure 2: schematic cross section of the dedicated test site used in phase 1. The area included in the image of Figures 3 and 4 are approximated by the rectangle.

The final processed image is shown in Figure 3, and an interpreted version is shown in Figure 4. Details of the acquisition and processing follow.
**Figure 3:** Nearly final processed seismic crosswell image as produced by ZSeis. Color background represents velocity model determined by crosswell transmission tomography (errors can be large near the wellbores at the edge of the image). Wiggle traces are the migrated seismic data from crosswell reflection imaging using the velocity model to provide transformations and migration. Various logs are displayed along the edges, at the locations of the Burch (on the left) and Stech (on the right) boreholes. Vertical axis is depth (not time). An interpreted version of this image is provided in the next figure.
Figure 4: Initial interpretation of the crosswell seismic image. The formation boundaries are indicated at their depths as shown by log data, at the edge of the image. The reef is indicated by shading, and is controlled by log data from the producing well (not shown) and by the change in seismic reflection character (not velocities). Notice that although there are distinct and coherent reflections visible within the reef, they are subdued in contrast to those outside of the reef. Notice also that some reflections appear to change phase within the reef even though they may be continuous with those outside.

The detail present in figures 3 and 4 can be contrasted with that found in a 3D (surface) seismic survey conducted over the site in 1983, as shown in Figure 5.
Figure 5: Two seismic lines extracted from a 3D survey conducted over the site in 1983. The line on the left is from an area that does not include the reef, and the line on the right includes the reef. (Tuning of certain evaporites vanishes where the reef exists, resulting in the more-chaotic reflection image at the reef.) The area covered by the crosswell surveys shown in Figures 3 and 4 is indicated approximately by the rectangle.

Notice that the typical wavelength in the crosswell data set is about 20 ft, while the wavelength in the surface 3D data set is about 400 ft (calculated from 0.02s period and 20,000 ft/s velocity). With additional processing, features smaller than 20 ft should be identifiable in the crosswell data.

Data Acquisition:
Data were collected for the main survey using source and receiver locations, every 10 ft, from about 2600 ft depth to about 6000 ft depth. A 0.35s sweep from 100 Hz to 3000 Hz was stacked 8 times at each depth. This geometry yielded coverage of the reef zone with reflection fold of over 200 and angles of incidence ranging from about 30° to 90°. A summary figure from ZSeis is shown in Figure 6, providing additional details.
Figure 6: Summary of data acquisition provided by Z-Seis.

The source was suspended in the Burch well, while the receivers were in the Stech well. The Burch well is cased only down to 2944 ft, and is open below that. (The Burch well needed to be cleaned out prior to running the survey, to remove salt that had precipitated in casing.) For each “fan” of shooting, the receiver string is held at a constant depth (using 10 receiver groups at 10-ft spacing for a total span of 100 ft) while the source is moved up the borehole, firing as it is moved. 8 shots, all within a 10-ft interval, are...
stacked for each source point. When the source has reached its shallowest point, it is
returned to depth, and the receiver string repositioned for the next “fan” of shooting.

One example of a common-receiver gather is shown in Figure 7, with a power spectrum
for the entire gather.

![Common-receiver gather and spectrum for a receiver at 5830 ft depth, and sources ranging from 4140 ft (at left edge) to 6000 ft (at right edge). The arrivals are clear and distinct, and reflections and converted phases are apparent even in this gather, prior to stacking. Notice that there is a set of arrivals with constant time (clearly visible at 0.126 s) when the source is deeper than about 5000 ft.]

The origin of a source-generated noise was of some concern in the field, and several small experiments were conducted to ensure that it was truly due to seismic (or pressure) waves in the formation or well. Figure 8 shows a common-source gather for a single source depth.
Figure 8: Common-source gather for a source at 5500 ft depth and receivers from 4610 ft to 6000 ft depth. The noise that was “flat” with time in the common-receiver domain is clearly seen to be traveling with tube-wave velocities in the common-source domain. These tube waves start at zero time at specific depths in the borehole.

The noise is seen to consist of tube waves which originate at zero time in certain locations in the wellbore. The fact that they are initiated in the receiver well at the time that the source is fired, and not at the time that the P-waves arrive at the well, indicates that they travel from the source well to the receiver well nearly instantaneously. We are investigating the possibility that they travel as electromagnetic waves from the source well, where the wireline cable is suspended below casing in open hole, and convert to tube waves upon arrival at the receiver well. We suspect that the long wireline cable acts as a sort of antenna. This investigation is ongoing, and additional speculation is premature at this time.

The tube-wave noise is easily removed from the data by standard array techniques such as median filtering, radon transforms, and f-k filtering. While it presents an interesting case study in its own right, it does not affect the data quality at all.
We note that the tube-wave noise only appears when the source is at depths greater than about 4500 ft. Figure 9 shows an example of a common-source gather at 3780 ft, showing no apparent tube waves.

![Common-source gather with a source depth of 3780 ft and receiver depths from 3800 ft to 5500 ft. Note that the large tube waves evident in Figure 8 are almost completely absent, suggesting that the long cable length in open hole is required to produce these large events.](image)

*Figure 9: Common-source gather with a source depth of 3780 ft and receiver depths from 3800 ft to 5500 ft. Note that the large tube waves evident in Figure 8 are almost completely absent, suggesting that the long cable length in open hole is required to produce these large events.*

A common-receiver gather is shown in Figure 10, at a receiver depth of 3810 ft (comparable to the source depth of Figure 9) with a power spectrum indicating that frequencies up to 3000 Hz were well-recorded. This gather was collected for a receiver depth in a thick salt layer. At this site, the carbonates and shales are so competent that salt is slow in comparison, resulting in the later arrivals in the middle of this gather, and refracted arrivals evident on either side. The tube-wave noise (again, with origin time of zero) is apparent for all source depths greater than about 4500 ft depth.
One additional data set was acquired, in order to ensure that we obtained the smallest-possible reflection angles of incidence. This consisted of what is called zero-offset data, for the entire well depths. In crosswell terminology, offset refers to differences in depths of receivers and sources, not to well separation. (See Figure 11 for a cartoon describing terminology.) Thus, zero-offset data refers to data collected with sources and receivers at the same depth. In this case, the source was moved up 100 ft, with 8 shots stacked every 10 ft, while the receiver string remained stationary with one receiver (group) located at the depth of the first shot. Then the receiver string was moved up 100 ft and the process repeated. Thus, we essentially collected a number of “fans” containing zero-offset data every 10 ft as well as offsets of 10 to 100 ft for each fan (every 100 ft). The zero-offset data will provide the narrowest-possible angles of reflection for reflectors beneath (or above) the depth of the source and receiver, while the “fans” associated with each shot point will allow the separation of upcoming and downgoing reflections.
Figure 11: Cartoon clarifying terminology for crosswell data. (Starbursts are sources, rings are receivers.)

a: Common-source gather. Direct ray paths are shown.

b: Common-receiver gather. Direct ray paths are shown.

c: Zero-offset gather. Direct ray paths are shown.

d: Zero-offset gather. Reflected-wave paths are shown for a single deep reflector. Note that the angle of incidence decreases for increasing differences in depth between the source-receiver location and the reflecting horizon.

e: Constant-offset gather. Direct ray paths are shown.
NOTE: Because “offset” refers to differences in depth, we will use the term amplitude-versus-angle (AVA) rather than amplitude-versus-offset (AVO) in reference to the pre-stack amplitude studies in crosswell domain.

Figure 12 shows a field display of the zero-offset dataset. Because the data have not been filtered for upcoming or downgoing reflections, the direct arrivals dominate. (Note the tube-wave noise present below 4500 ft depth.)

Figure 12: Zero-offset (actually, this display is for a constant-offset of -10 ft), with (direct) first-arrivals indicated by the yellow line. Note the tube waves below about 4500 ft depth. This dataset has not been filtered for upcoming or downgoing waves, so the section is dominated by direct arrivals. Processing will bring out the AVA character of the reflections.

The variations in angle of takeoff at the source and angle of incidence at the receiver are important because these angles vary so greatly in the crosswell geometry. The source is a piezo-electric transducer, with a strength that varies with angle. The strongest radiation is emitted perpendicular to the axis of the tool; in this experiment, the tool is vertical, and the strongest radiation is in the horizontal direction. The strength varies, to a first-degree approximation, in a sinusoidal manner. Figure 13 shows the source strength as a function of angle of takeoff, with a long-diagonal path used for demonstration.
**Figure 13:** schematic diagram showing radiation pattern (energy is proportional to length of dark circles) and long ray path tested between 500 ft and 6500 ft. The dark circles show the amplitude of the signal; the light circles are simple protractors superimposed in order to provide a visual indication of angles of takeoff and incidence.

**Data Processing:**
There are two important aspects to recognize from the phase 1 data set so far:
- The imaging quality is excellent, with a wide band of angles
- The frequency content of the data is outstanding.

Z-Seis performed the processing of the data to provide the image shown in Figure 3. The processing of crosswell data is not commonplace, but it is well-described in the literature. The reader is referred to Lazarotos, 1993, and papers derived from that work.

The image shown in Figure 3 was derived from a stack of all (upward) reflections with angles of incidence within a certain range. The partial-stack images of Figure 14 demonstrate some of the effect that AVA can exert.
Figure 14: Two stacks of the data. The image on the left was stacked using angles that ranged from 55° to 65° and the image on the right included all angles from 40° to 70°. The differences are due largely to differences in AVA response. (Vertical scale is depth in thousands of feet.)

At first glance it appears that the differences due to AVA are most pronounced within the area of the reef structure, but this may simply be an optical illusion resulting from the lower-amplitude reflections found there. Analysis of AVA data will form the basis for most of the continuing work on this dataset.

Modeling of Wide-Angle Reflections:
In addition to the field data, its processing, and its interpretation, we have been preparing for the post-processing and analysis of the data in terms of wide-angle AVA. Whereas most surface seismic data (and all standard analysis techniques) are used over reflection angles of 30° or less (at most 45°), almost all of the data within a crosswell seismic set is in the angle range of 40° or greater. It has been the experience that the processing that yields optimal images for crosswell data consists of narrow-angle gathers;
this is probably due to the wavelet distortion that occurs at wide angles, and selecting too broad an angle range will tend to stack wavelets of different phases. In order to prepare for the analysis of the seismic data we acquired, we have written Matlab code to predict, using the full (not simplified) Zoeppritz equations, reflection amplitudes of P-P and P-S waves. An example output is shown in Figure 15a and 15b.

**Figure 15a:** Amplitude response of P-wave reflections as a function of angle for a typical reflection in the sequence encountered within the reef play.

**Figure 15b:** phase shift for the case shown in Figure 5a. Note the large phase shifts at angles greater than about 60° in this case.
Results and discussion:

The data quality of the crosswell seismic experiment exceeds expectations; in many places, the resolution will be finer than 20 feet, perhaps much finer. There is strong evidence of AVA effects even at this point in the analysis, and the effects are apparent within the reef structure. Within the reef, we might expect to see gas-oil contacts within some compartments, or across the reef as a whole. It is informative to investigate the response that we could expect for this contact in a competent carbonate rock. The solution to Zoeppritz equations for the idealized simple case of an overlying gas-saturated limestone (density = 2.6 g/cc; Vp=20,000 ft/s; Vs=12,000 ft/s) with a reflection from its interface with an oil-saturated limestone (density=2.7 g/cc, Vp=21,000 ft/s; Vs=12,000 ft/s) is shown in Figure 16.

![Zoeppritz solutions for the case of an idealized gas-oil contact within a limestone reef with low porosity.](image)

Notice that the critical angle is 74°, well beyond the range that can be collected from surface seismic methods. Notice also that the amplitude of the reflection is very small for the range 0°- 60°, and would likely be imperceptible on surface seismic data. On the other hand, the amplitude is large within the typical stacking range for crosswell seismic imaging, particularly within the range of 60° - 70°. Beyond 70°, the amplitude of the reflected P-wave is close to 1, but the phase shift slowly increases to 180° at 90° angle of incidence. Thus, we should expect to see fluid contacts within the reef if they exist at a scale visible to crosswell observations.

![Zoeppritz solutions for the case of an idealized gas-oil contact within a limestone reef with low porosity.](image)

Figure 17 shows a detailed comparison of the partial stacks previously presented in Figure 14. There is more character within the reef section for the stack that includes a wider range of angles. Our investigation is continuing, but if it turns out that some of the reflections are apparent only in the widest-angle components, it may also turn out that these are indicative of fluid contacts.
Figure 17: Close-up of reef section of the two partial stacks from Figure 14. Notice that there is more character in the stack that includes a wider range of angles. (Vertical scale is depth in thousands of feet.)

Conclusions:

At this point, the data demonstrates:

- Current borehole sources are more powerful than anticipated.
- The upper limit of frequency is at least 3 kHz, and apparently higher.
- High-quality images can be obtained.
- The narrowest angles, which depend on extremely long reflected-ray paths are determined by borehole geometry more than by source and receiver characteristics.

The modeling demonstrates:

- Reflections from subtle contrasts, such as fluid contacts in competent rock, may be visible on wide-angle data from crosswell surveys, even though they would be invisible on surface seismic data.
- Phase shifts are important and should be used in processing and interpretation.
The project is highly successful to date. Processing continues and interpretation has begun. The technology shows great promise for identification of internal compartments and fluid distribution within carbonate reefs, ultimately allowing better targeting of sidetrack wells and reservoir engineering practices.

**MILESTONES:**

All milestones have been met on schedule. The data collection took place in early summer of 2005; initial processing to obtain a crosswell image was complete in September 2005, and data are being processed in detail for AVA at this time. Site selection for phase 2 is beginning (see next section).

**Plans for phase 2:**

Site selection for phase 2 has begun. We have contacted a number of operators producing from Niagaran reefs in the Michigan basin, and many are extremely interested in this technology. Our request for two boreholes with at least a partial reef in between is not as restricting as we had thought it might be – there are many such pairs of wells. The final selection of site will probably involve borehole availability at the time that the survey should be conducted. The survey will take place only after phase 1 is completed to the extent that all lessons regarding maximum and minimum angles, sweep length, frequency content, and stacking parameters, have been learned and can be applied.

We plan to conduct the field work for acquisition of phase 2 during the summer of 2006. This schedule continues to be reasonable and feasible.

**COST AND SCHEDULE STATUS:**

The budget for the first year was just adequate to conduct the work planned for the first year. Continuing work, including additional processing on the first-phase data set, is dependent on receipt of funding for the second year. Phase 1 should conclude during the second year, as scheduled, after processing and analysis is complete. We have budgeted a PhD student, using, in part, cost-share funds from Michigan Technological University. So far, we have been working with an MS student and an undergraduate student, using other funds not previously budgeted for this effort; we are still identifying an appropriate PhD student to work through all remaining phases of the project.

Note that the phases do not coincide with fiscal years. Phase 1 continues into year 2, and Phase 2 takes place in years 2 and 3, starting late in year 2, but with the bulk of the costs – associated with field acquisition – occurring during year 2. Year 3 completes Phase 2 processing, interpretation, and analysis, and all technical transfer. Also note that the costs are not equally distributed throughout each year, but within each year costs are concentrated at the time of field work.

The following table provides the details for the Budget in a convenient form.
Budget Information for DOE Crosswell AVO project
E21750 (Yr 1), E21761 (Yr 2), E21762 (Yr 2 cost share), E34507 (graduate student support)

Budget Data as of September 30, 2005

<table>
<thead>
<tr>
<th>Phase / Budget Period</th>
<th>Approved Spending Plan</th>
<th>Actual Spent to Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DOE Amount</td>
<td>Cost Share</td>
</tr>
<tr>
<td>From</td>
<td>To</td>
<td></td>
</tr>
<tr>
<td>Year 1 10/01/04</td>
<td>09/30/05</td>
<td>376,064</td>
</tr>
<tr>
<td>Year 2 10/01/05</td>
<td>09/30/06</td>
<td>54,500</td>
</tr>
<tr>
<td>Year 3 10/01/06</td>
<td>09/30/07</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>430,564</td>
</tr>
</tbody>
</table>

Note: This is a partial award of year two funds – the total Year 2 funding is budgeted at $286,291 in DOE share and $63,814 in cost share.

Publication Notes:

While we were funded on this project, a paper “The Rapid Rise of Reservoir Geophysics” was invited by the Society of Exploration Geophysics for publication in a special 75th anniversary issue of The Leading Edge. The manuscript was provided to NETL for review. The paper was published in a Special Edition of The Leading Edge in October. Two copies of the paper are being provided to AAD Document Control.

Field Picture:

The picture on the following page shows the field operation at the receiver well.

References:

Figure 18: Picture of the Michigan Tech field crew during the experiment at the test site in 2005. From left: Wayne Pennington (PI), Sean Trisch (graduate student), Roger Turpening (co-PI), and Josh Richardson (undergraduate student). The Z-Seis recording truck is in the background, with the receiver string suspended 3500 ft below the surface of the Stech well. Photo by Josh Richardson.