4D Seismic Monitoring of In-Situ Combustion of Heavy Oil Reservoirs*

Diego Morales¹, Trino Salinas¹, and Gabriel Alvarez¹

Search and Discovery Article #41529 (2015)**
Posted February 2, 2015

*Adapted from oral presentation given at Geoscience Technology Workshop, Expanding Unconventional Resources in Colombia with New Science - From Heavy Oil to Shale Gas/Shale Oil Opportunities, Bogota, Colombia, December 10-11, 2014

**Datapages © 2015 Serial rights given by author. For all other rights contact author directly.

¹Pacific Rubiales, Bogota, Columbia (galvarez@Pacificrubiales.com.co)

Abstract

In-situ combustion is a process that is quickly gaining interest in the industry as a relatively straightforward EOR method, especially in heavy-oil reservoirs. Of critical importance to the success of this process is the effective monitoring of the reservoir zone affected by the combustion. Since in-situ combustion alters the elastic properties of the rocks and generates combustion gases (in addition to the air injected in the reservoir), the seismic response of the affected area is expected to be different before and after this process.

We will show in this presentation the results of the first 4D seismic project carried out in Colombia as part of the STAR pilot project of synchronized in-situ combustion in the Eastern Llanos basin in Colombia. We will present an overview of the design, acquisition and processing of the seismic data and show how the 4D seismic generates a clear three-dimensional image of the area affected by the combustion process. In particular, we will show that the affected area is nowhere close to the nice spherical shape we would expect if the reservoir were homogeneous and isotropic. Instead, the affected area shows preferential flow directions and flow barriers, which demonstrate the heterogeneity and anisotropy of the thin reservoir unit. This information is of the utmost importance to synchronize and optimize the combustion process by optimally placing injector and producer wells to reduce bypassed oil.
4D seismic monitoring of in-situ combustion of heavy oil reservoirs

Diego Morales
Trino Salinas
Gabriel Alvarez
Seismic monitoring (4D seismic): overview

• It’s the repeated acquisition of a seismic volume at “reasonable” time intervals.

• Absent a physical process that could alter the subsurface, the seismic volumes should be the same (or nearly so).

• If a physical process capable of altering the subsurface (steam injection, in-situ combustion, etc) is carried out, the difference between the seismic volumes should reflect the effect of such process.

• The repeated seismic volumes allow the monitoring of the physical process as a function of repetition time interval.
What do we obtain from the 4D-3C seismic?

- Seismic volumes of each repetition and volumes of the difference between the base case and each repetition and between repetitions.

- The difference volumes can be obtained for any elastic parameter associated to the propagation of the seismic waves: seismic amplitudes, impedances, elastic modulii (Young’s modulus, volumetric modulus, stiffness modulus, etc), Poisson’s ration, Vp/Vs ratio, etc.

- These volumes provide direct information about the geometry, depth and thickness of the subsurface layers affected by the physical process.
Project Location. Llanos Basin, Colombia
Location Map
Seismic monitoring. Geometry.
Main acquisition parameters

Survey area: 4.7 km² ~ 2.2 by 2.2 km

Bin size: 6x6 m².

Nominal fold 24.

Source line distance = Receiver line distance = 216

Source type: explosives. 1 hole, 10 m, 1800 gr.

Recording patch: 10 lines, 180 ch each.

Receiver type: single 3C geophone buried 10 ft.
Acquisition Geometry – Base case
Source map: base-case (red), monitor 1 (blue)
Receiver map: base-case (red), monitor 1 (blue)
Map of sources and receivers: base case
Map of sources and receivers: monitor 1
Seismic monitoring. Data processing.
Seismic processing: 4D-3C

Data processed at CGG in Calgary. Joint inversion in CGG Houston.

- PSTM PP component
- PSTM PS components
- PP elastic simultaneous inversion
- Joint PP-PS simultaneous inversion

Carried out for the base case and each monitoring. Difference volumes computed for all attributes.
Comments on seismic processing

“Standard” land-data processing sequence. Emphasis on repeatability on processes and parameters.

Compensation of wavelet phase and amplitudes between surveys.

Compensation for time-shift differences (statics) between surveys.
Filter operator for wavelet matching
Wavelet calibration

Reference Volume Wavelet

Analysis Volume Wavelet

Match Filter Wavelet

Analysis Volume Wavelet after Filtering

Amplitude

Amplitude

Amplitude

Amplitude

BASE

Monitor

Operator

Monitor match
Cross-correlation between surveys
Time shift (statics) correlation
Comparison of matched volumes
Seismic monitoring. Difference in PP volumes
Inline section inside the combustion area

Seismic volume
July 2012
(Baseline)

Seismic volume
November 2013
(Monitor 1)

Difference (monitor1-baseline)
November 2013

Top of basal sands

Amplitude
- 14000
- 10000
- 6000
- 2000

High

840 ms
860 ms
880 ms

Low

100 m

Pacific
Rubiales Energy
Xline section inside the combustion area

Seismic volume
July 2012
(Baseline)

Seismic volume
November 2013
(Monitor 1)

Difference (monitor1-baseline)
November 2013

Amplitude

- High
- Low

- 840 ms
- 860 ms
- 880 ms

Top of basal sands

100 m

14000
10000
6000
2000
Inline section outside the combustion area

Seismic volume
July 2012 (Baseline)

Seismic volume
November 2013 (Monitor 1)

Difference (monitor1-baseline)
November 2013

Amplitude

High

Low

14000
10000
6000
2000

100 m
“Horizon slice” from difference volume (amplitudes): monitor 1 – baseline

Volume flattened at top of basal sands

HS taken at formation top

Amplitude

High

Low
“Horizon slice” from difference volume (amplitudes): monitor 1 – baseline

Volume flattened at top of basal sands

HS taken 2 ms below formation top
“Horizon slice” from difference volume (amplitudes): monitor 1 – baseline

Volume flattened at top of basal sands

HS taken 4 ms below formation top
"Horizon slice" from difference volume (amplitudes): monitor 1 – baseline

Volume flattened at top of basal sands

HS taken 6 ms below formation top

6 ms ≈ 24 ft
“Horizon slice” from difference volume (amplitudes): monitor 1 – baseline

Volume flattened at top of basal sands

HS taken 8 ms below formation top
3D amplitude anomaly (Geobody)

QF-IV-2 injector
QF-162D
QF-164D

QF-137D
QF-140D
QF-139D

Geobody of amplitude anomaly (Difference)
Seismic monitoring. Interpretation.
What do the seismic anomalies represent?

- Changes in the elastic properties of the rock and fluids.

- Fluids seem to account for most of the observed effects. Changes in rock matrix seem to be “small” or not significant enough to alter the elastic modulii within the seismic resolution.

- Fluid effects come from air injection, combustion gasses, steam generation.
Amplitude difference (Monitor 1-Base) PS, PP
Delay-time effect

Monitor

Delay

Base

Pacific Rubiales Energy
Time and amplitude differences: Monitor 1-base

Time difference (Delay)  Amplitude difference
Conclusions

• Surface 4D seismic is an effective tool for monitoring the effects of in-situ combustion of Quifa heavy oil reservoir.

• The most evident changes in the seismic parameters are in amplitudes and delay times.

• Comparison between anomalies in PP and PS may help discriminate effects due to changes in the rock matrix vs. changes due to fluids.