Modelling of 4D Seismic Data for the Monitoring of the Steam Chamber Growth during the SAGD Process

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Introduction

SAGD: Steam-Assisted Gravity Drainage

Fluvial/estuarine reservoirs are not homogeneous

Impact on the steam chamber development?
Introduction

4D seismic (Ex: Christina Lake)

Map views of 4D seismic amplitude difference

Steam injection

- reduction of viscosity and mobility ratio
- but also: rock and fluid expansion, compaction, oil vaporization,…

between 2001 and 2004 surveys

between 2001 and 2005 surveys

Zhang et al., 2005
What is SeisMovie™?

- SeisMovie records a « movie » of production
- Permanent network of buried sources and receivers
- High repeatability: tiny changes in reservoir can be measured
- Continuous signal monitoring to observe short period variations
- A wide range of applications
  - Steam and water injection
  - Gas storage
  - CO2 disposal
  - Environmentally sensitive areas
Introduction

Project objectives

- Imaging of the steam chamber evolution from 4D seismic data at early times of SAGD steam injection phase
- Improvement of the interpretation of SeisMovie™ surveys in heavy oil and bitumen production
- Improvement of the understanding of physical laws driving the petro-elastic model during steam injection
- Develop a workflow for the interpretation of 4D seismic data, based on a real field case
Workflow

1. Construction of the full-field static model
2. Reservoir-geomechanics coupled modeling
3. Seismic modeling and sensitivity tests
Illustration on a synthetic case

1. Construction of the full-field static model
   Geological model and static properties

2. Coupled modeling
   Reservoir simulation (PumaFlow)
   Geomechanical modeling (Abaqus)

3. Seismic modeling
   Impact of thermal production on PEM (petroelastic model)
1- Construction of the full-field static model

→ Geological model and static properties
Hangingstone Field

- Athabasca region (Alberta, Canada)
- McMurray Formation
- Oil viscosity 1,000,000 cp (@ reservoir condition)
- Oil density 8° API
- 16 horizontal well pairs
- 50 vertical observation wells
- 10 cored wells
- Production data (90 months)

All public data
Well Log Interpretation

McMurray Fm.

- Lithofacies 1
- Lithofacies 2
- Lithofacies 3
- Lithofacies 4
- Lithofacies 5

- Open bay shales
- Stacked tidal flats, Channels and bars
- Tidal ravinement
  Stacked meandering channels
  With tidal influence
- Amalgamated fluvial Braided channels
- Channel belt incision
  Coastal plain?
- Base Cretaceous unconformity

0, Aberdeen, Scotland
Geostatistical Simulation of Facies Distribution

- 5 lithofacies
- Method: Truncated Gaussian
- 90 layers
- X,Y: 10m x 10m
- Z: 0.5m
- 5.10^6 cells
2. Coupled modeling

- Reservoir simulation (PumaFlow)
- Geomechanical modeling (Abaqus)
Properties exported to the reservoir model
Very fine reservoir grid (235,000 cells):
X: 10x2.5m; 50x1m; 10x2.5m
Y: 41x20m
Z: 61x0.5m; 5x1m; 5x2.5m
Block size 900m x 100m x 320m
Operating conditions in the wells for SAGD modeling

- Warm up phase
  - Four months @ constant T = 220°C
- Steam injection: up to 6 years
  - Real injection-production history at wells
  - Steam trap control implemented
Field data: (flow rates)
Production history of E well pair

![Graph showing steam and oil+water production over time from start of steam injection.](graph.png)
Oil & Water production in the E well pair producer

Cumulative oil production (m³)

- Field data
- Simulation

Time from start of steam injection (days)

Reservoir simulation with PumaFlow

6 Years
% of steam rate along the injector

Grid section number

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40

heel to toe

5 days
10 days
30 days
61 days
92 days
122 days
183 days

% of steam rate injected

0 1 2 3 4 5 6 7 8 9 10 11 12

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Impact of the shale mechanical behavior on the geometry of the steam chamber

Shales remain a barrier
One-way coupling

Explicit coupling
(update of permeabilities)
Shales can reach rupture
Negative thermal expansion coefficient

⇒ Yielding of shale materials

Temperature in section 5

**One-way Coupling**

Temperature field is stopped by the shale inclusion

**Explicit Coupling**

Temperature field goes through the shale inclusion
Negative thermal expansion coefficient

Yielding of shale materials

Pore Pressure in section 5

One-way Coupling

Strong overpressure above shale breaks: T is high, oil expands but can not be produced

Explicit Coupling

Homogeneous over-pressure as for clean sections
Update of the petroelastic model

Materials
Temperature
Pore Pressure
Effective Stress

6 Months
3- Seismic modeling

*Impact of thermal production on PEM (petroelastic model)*
Velocities and impedance calculation

Geomodeler (Geometry, Parameters...)

Reservoir modeling
- input: $\text{visco}(T)$
- output: $P, T, S$

Geomechanical modeling
- input: $P, T$
- output: $\sigma_{\text{eff}}, \phi$

Fluid parameters
- $K_{fl} = f(P, T, S)$
- $G_{fl} = f(P, \text{visco}(T), S)$
- $\rho_{fl} = f(P, T, S)$

Grain parameters
- $\rho_{gr}$
- $K_{gr}$
- $G_{gr}$

Incompressibility & shear modulus
- $K_{nd} = f(K_{d}, K_{gr}, K_{fl}, \phi)$
- $G_{nd} = f(G_{d}, G_{gr}, G_{fl}, \phi)$

Drained Modulus
- $K_{d} = f(\sigma_{\text{eff}})$
- $G_{d} = f(\sigma_{\text{eff}})$

Density
- $\rho = \rho_{gr} \ast (1 - \phi) + \rho_{fl} \ast \phi$

P and S wave seismic velocities
- $V = f(K_{nd}, G_{nd}, 1/\rho)$

Acoustic impedance & reflectivity
1D seismic modeling (reservoir zone):
Lithofacies (top), reflectivity coefficients convolved by a 80 Hz Ricker (bottom)
Synthetic Seismograms in time

At the initial stage and after 6 months of production

1D convolution, Ricker - 80 Hz

March 2000

January 2001

500 m
Horizontal slices of P-wave at the injection well (depth -314.5m)

P-wave seismogram difference $t-t_0$

Difference of amplitude with the base survey at initial time after depth conversion:
- 2-1: end of warm-up
- 3-1: 1st month of prod.
- 4-1: 2nd month of prod.
- 5-1: 4th month of prod.
- 6-1: 6th month of prod.
SAGD Model after 3 Years of Production

- Lithofacies distribution
- Oil saturation
- P-wave seismogram
Conclusions 1/2

- Fully integrated study from static to dynamic modeling
  - Geology, petrophysics, geomechanics, petroacoustics
- Simulations of full production history
  - Steam rate satisfied in the injector
  - Oil and water rate satisfied in the producer
  - Proportion of oil and water respected
  - Lateral steam connection between sections is taken into account
Conclusions 2/2

- Impact of heterogeneities on steam chamber development
  - Influence of shale beds on the steam chamber development is clear on 3D visualizations
  - Mechanical behavior of shales needs to be further characterized

- Seismic modeling
  - Petroelastic modeling shows realistic images
  - Model updates according to dynamic properties evolution

- Monitoring
  - Improved understanding expected through Seismmovie interpretation

- Further work: integration of the real seismic data