GLOBAL PETROLEUM SHOW 2019

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CALGARY, CANADA

AnBound Energy Inc.

THE KEY TO PREDICTIVE RESERVOIR SIMULATION OF EOR PROJECTS

Dubert Gutiérrez, AnBound Energy Inc.

GPS19-170

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Similarities Between an EOR Project and a Spouse

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Outline

- Hot Water Injection Pilot (SPE-174491-PA)
- Water Injection & Polymer Injection (SPE-165234-PA)
- In-Situ Combustion Pilot (SPE-174455-PA)

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Motivation

- Laboratory data often treated as “gospel” in field-scale EOR modelling
- Increase in use of data-driven analytical models, in isolation from physical theory
- Lack of predictability of history matched simulation models
- Modelling opportunity for EOR Pilots
  - Data availability and advancements in reservoir simulation technology (i.e. hardware and software)

Hot Water Injection in the Pelican Lake Field (Alberta)

- Discovered: 1978
- Wabiskaw “A” sand
- Thin formation: two to six meters
- Oil viscosity: 600 to 80,000+ cp
- Horizontal drilling: late 1980s
- Multilateral wells: early 1990s
- Waterflood: early 2000s
- Polymer injection: mid 2000s
- Hot water injection pilot: June 2011

TABLE 1—WABISKAW RESERVOIR CHARACTERISTICS

Depth	300–450 m	985–1,475 ft
Thickness	1–9 m	3–30 ft
Porosity	28–32%	28–32%
Permeability	300–5,000 md	300–5,000 md
Oil saturation	60–70%	60–70%
Temperature	12–17°C	54–63°F
Initial pressure	1800–2600 kPa	260–380 psi
Oil gravity	11.5–16.5°API	11.5–16.5°API
Solution Gas/Oil Ratio	4–6 m^3/m^3	22–34 scf/STB
Dead-Oil viscosity	800–80,000 cp	800–80,000 cp
Live-Oil viscosity	600–50,000 cp	600–50,000 cp

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Overview of Hot Water Injection Pilot

- 3 Horizontal wells
  - 2 Hot water injectors (edges)
  - 1 Producer (middle)
- 3 Vertical observation wells
- Hot water circulation in producer
  - Insulated coiled tubing
  - Hot fluid is delivered to the toe of the producer
  - Oil is stimulated/mobilized through conduction heating

Areal View

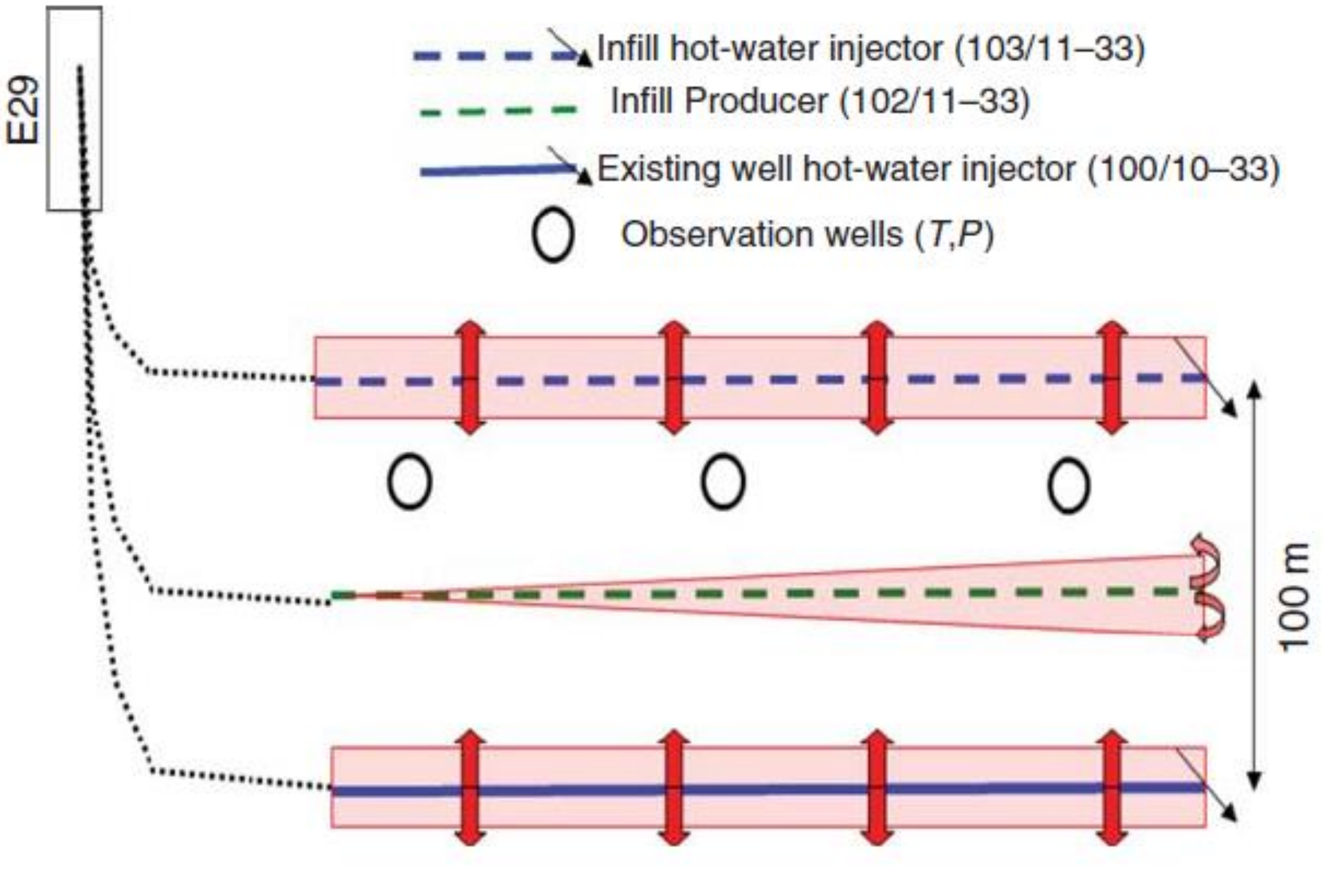

Fig. 4—Phase 3: hot-water injection and circulation.

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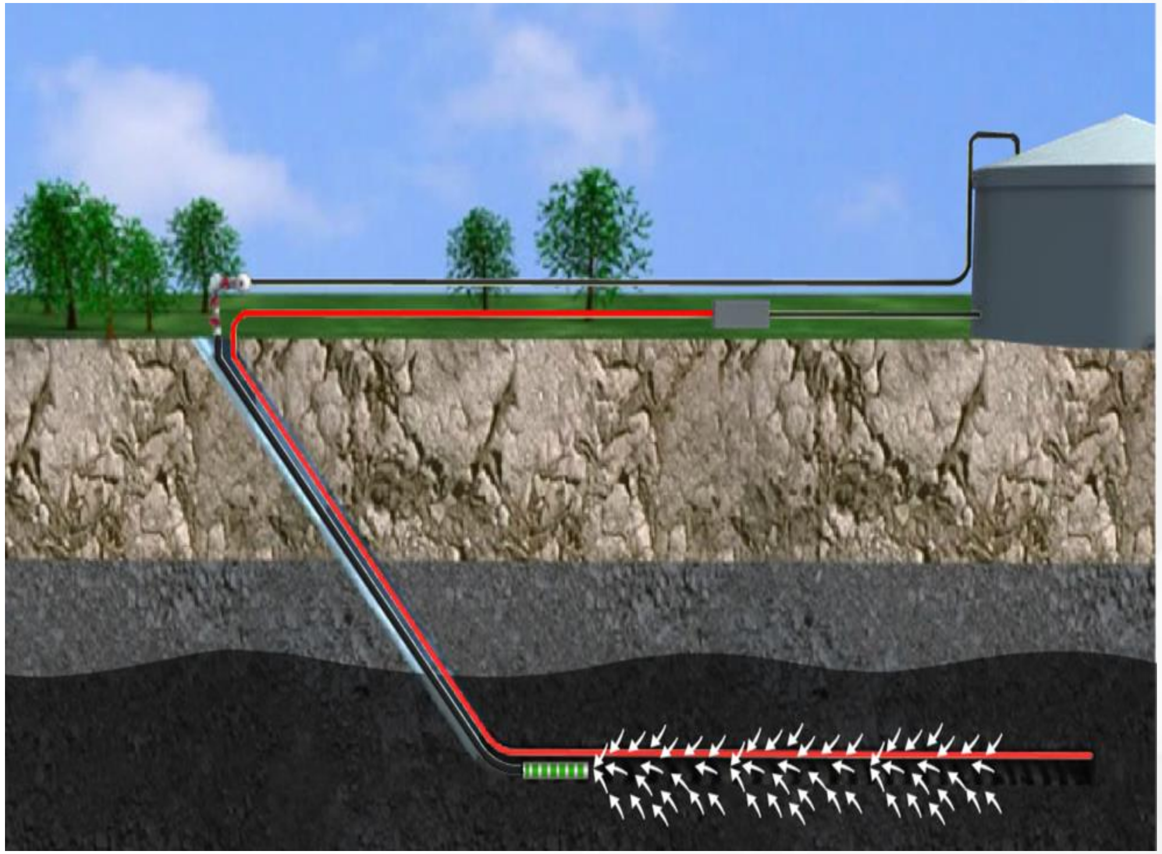
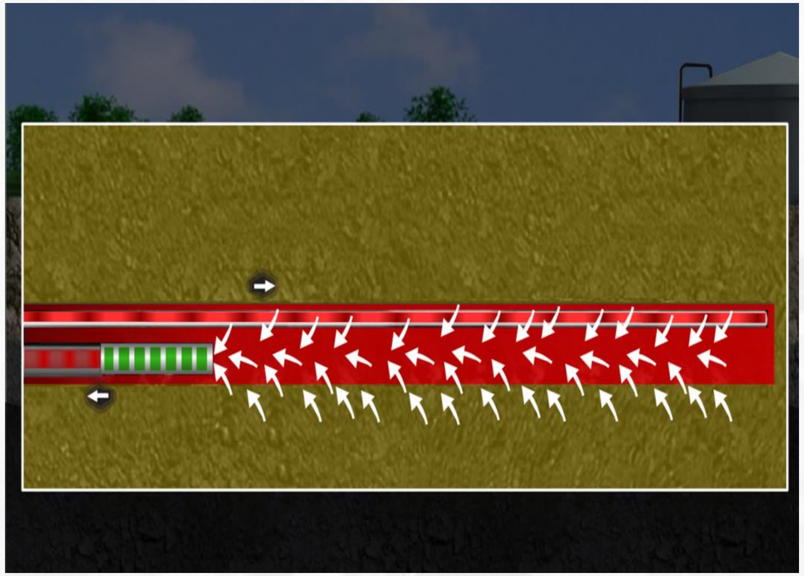
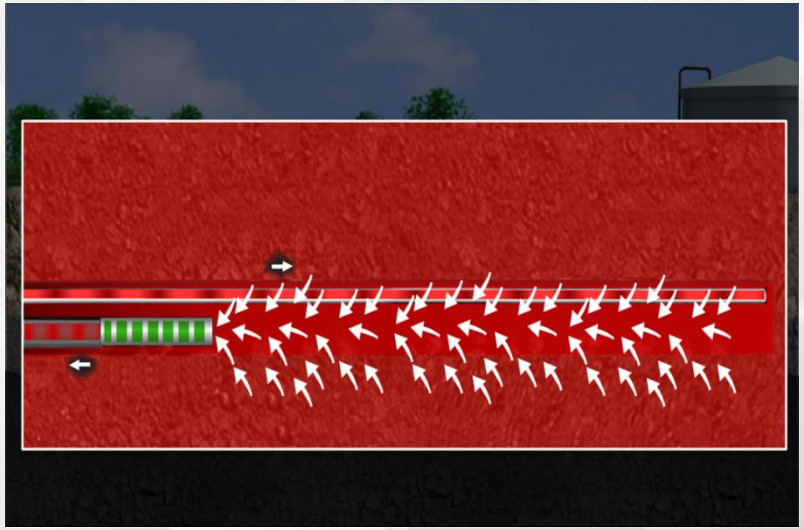
Mechanics of Hot Water Circulation







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Oil Viscosity Variation in Pilot Area

Well	Test Date	°API at 15°C	Oil Viscosity at 15°C (cp)
Heel Observation Well 100/12-32	9 December 2011	13.4	9,166
	12 April 2012	13.2	8,218
	12 April 2014	13.2	8,462
Middle Observation Well 100/09-32	9 December 2011	14.8	4,316
	12 April 2012	15.4	2,446
	12 April 2014	16.6	1,233
Toe Observation Well 100/11-33	9 December 2011	15.5	2,517
	12 April 2012	15.6	1,977
	12 April 2014	15.8	1,832

Table 1—Observation-well produced-oil viscosity.

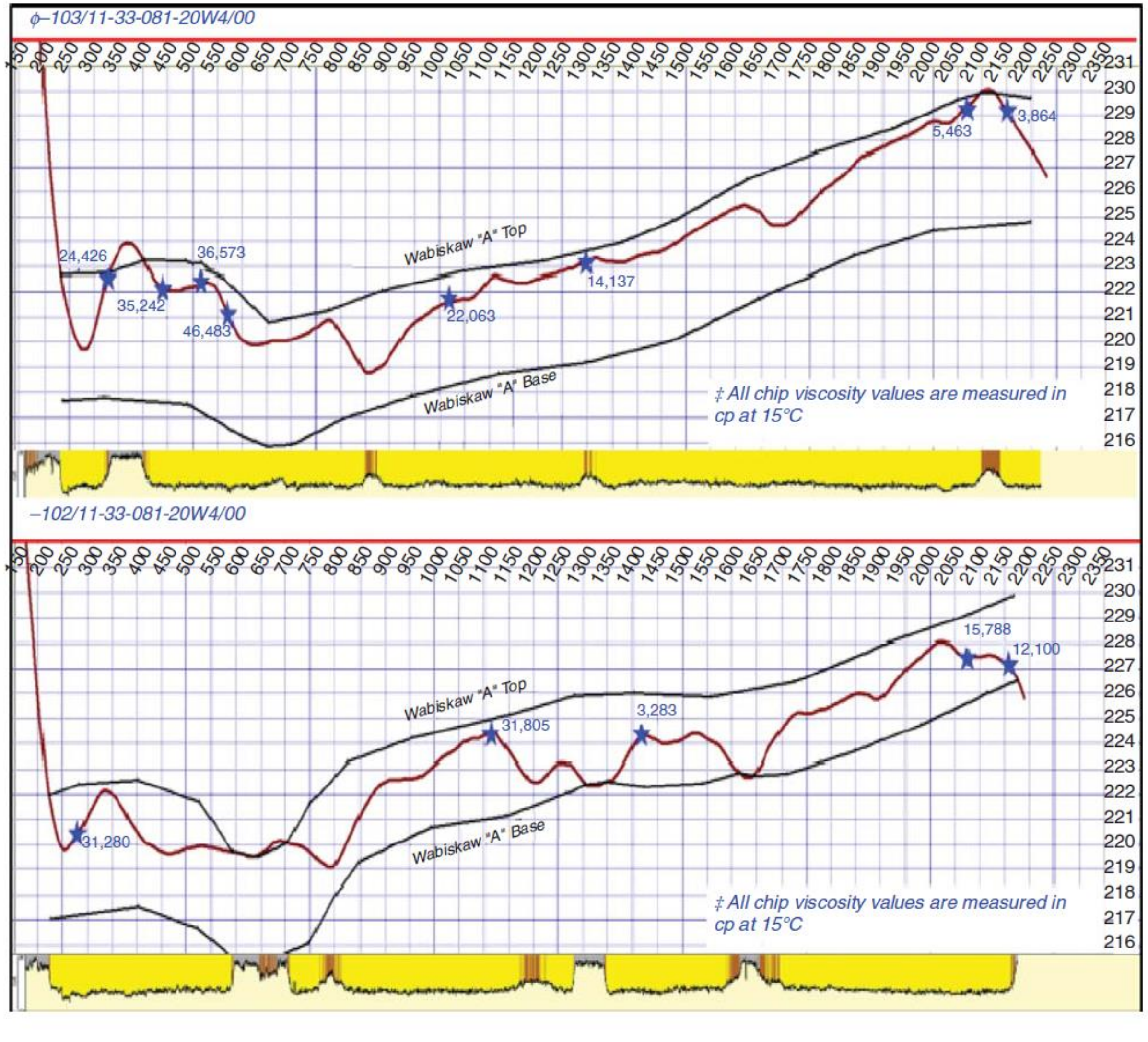

Fig. 9—Chip-sample viscosities along well paths.

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Reservoir Simulation Challenges & Opportunities

- Good news
  - Structurally very simple
  - Reservoir properties at pilot site seem uniform and consistent between wells
  - A simple homogeneous (but anisotropic) "box" model could be used
  - Good field data gathering and pilot surveillance

- Not so good news
  - Heterogeneity in oil viscosity in pilot area
  - Viscosity of produced oil samples are not representative of in-situ reservoir oil (i.e. lighter oil fractions are produced while heavier fractions remain in-situ)
  - Conventional oil viscosity modeling approach might not be appropriate

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How to Model Oil Viscosity Distribution?

- 3 Different oil viscosity distributions were considered. What is the in-situ oil viscosity required to obtain the produced oil viscosity?

Reservoir Simulation Models – Live Oil Viscosity

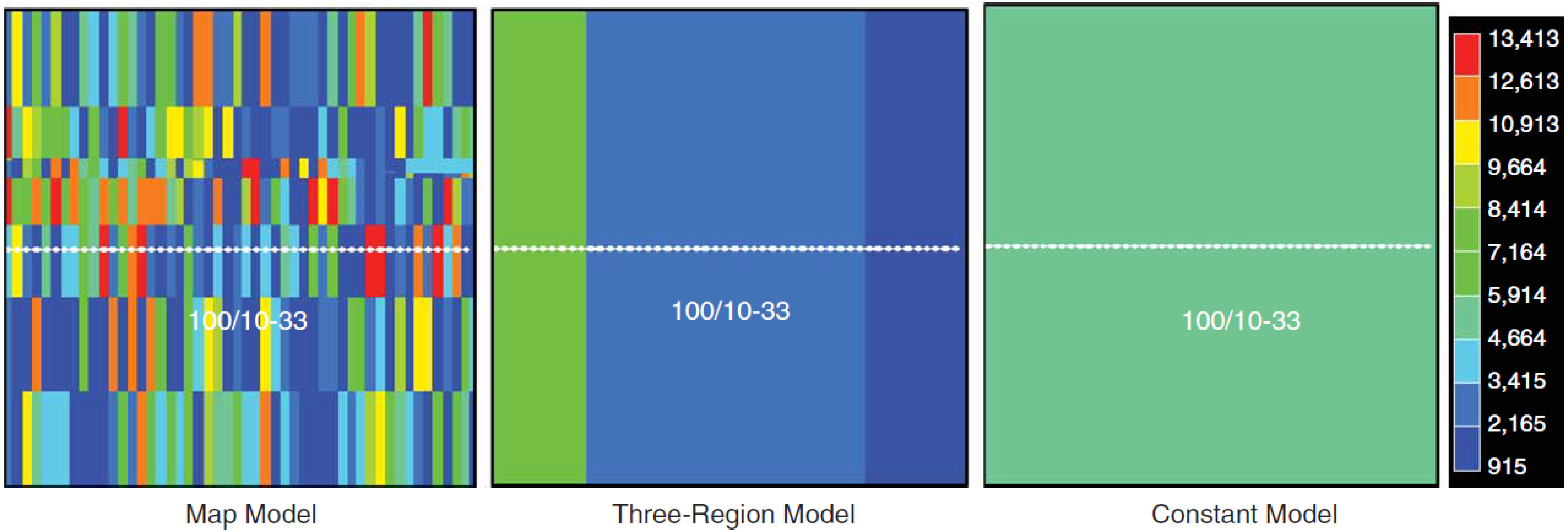

Fig. 17—Plan view of different oil-viscosity models (live-oil viscosity).

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History Matching Results – After SPE-174491-PA

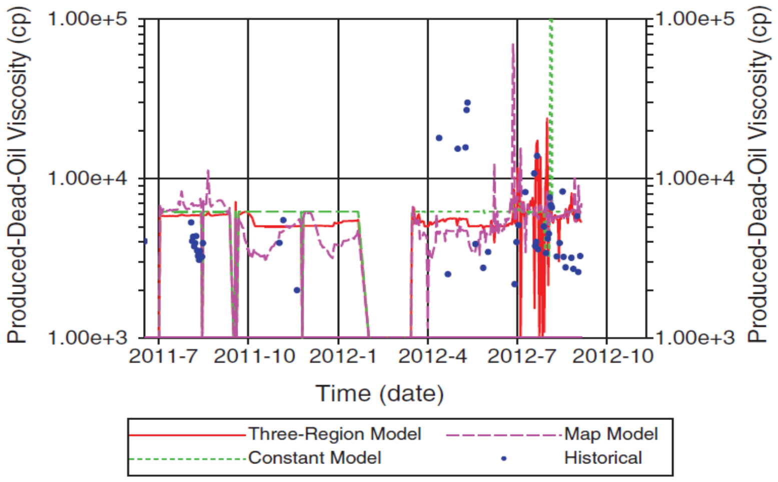

Fig. 20—Produced-oil viscosity.

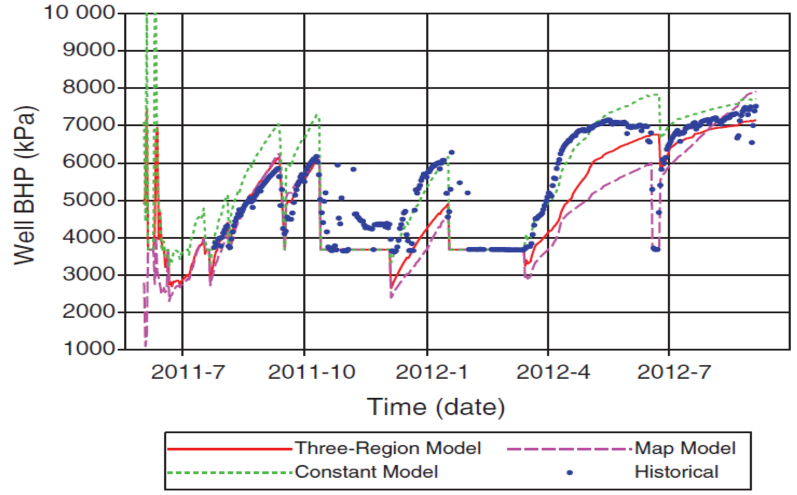

Fig. 18—BHP of thermal injector.

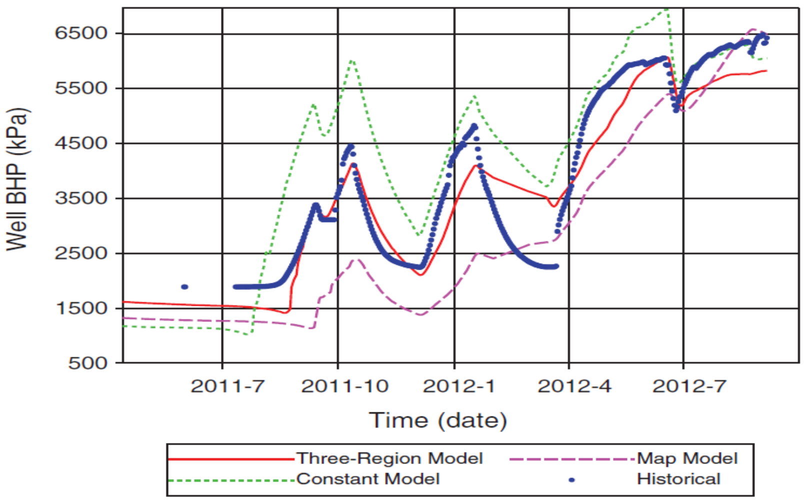

Fig. 21—Heel-observation-well pressure.

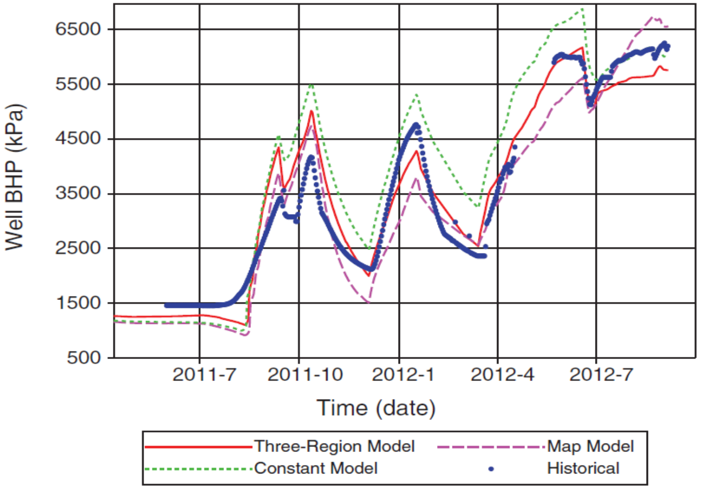

Fig. 23—Toe-observation-well pressure.

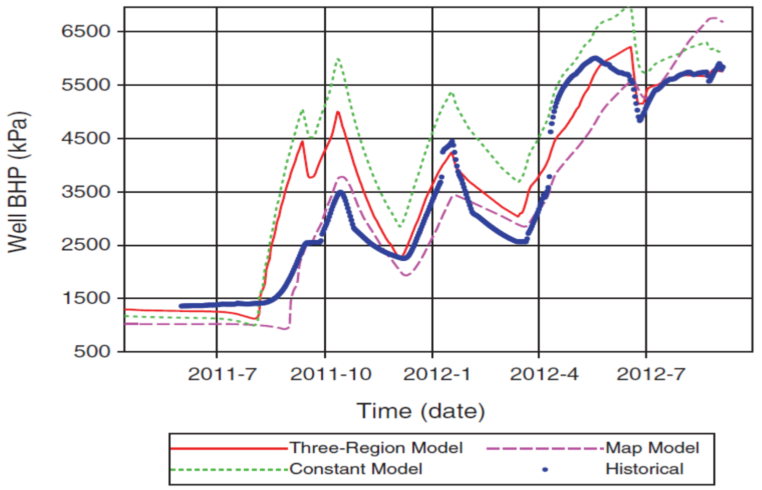

Fig. 22—Middle-observation-well pressure.

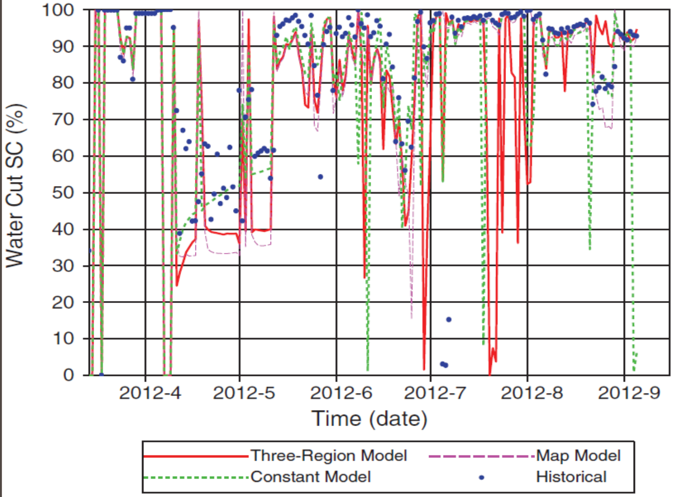

Fig. 25—Water cut in circulation well.

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Reservoir Simulation Forecasts

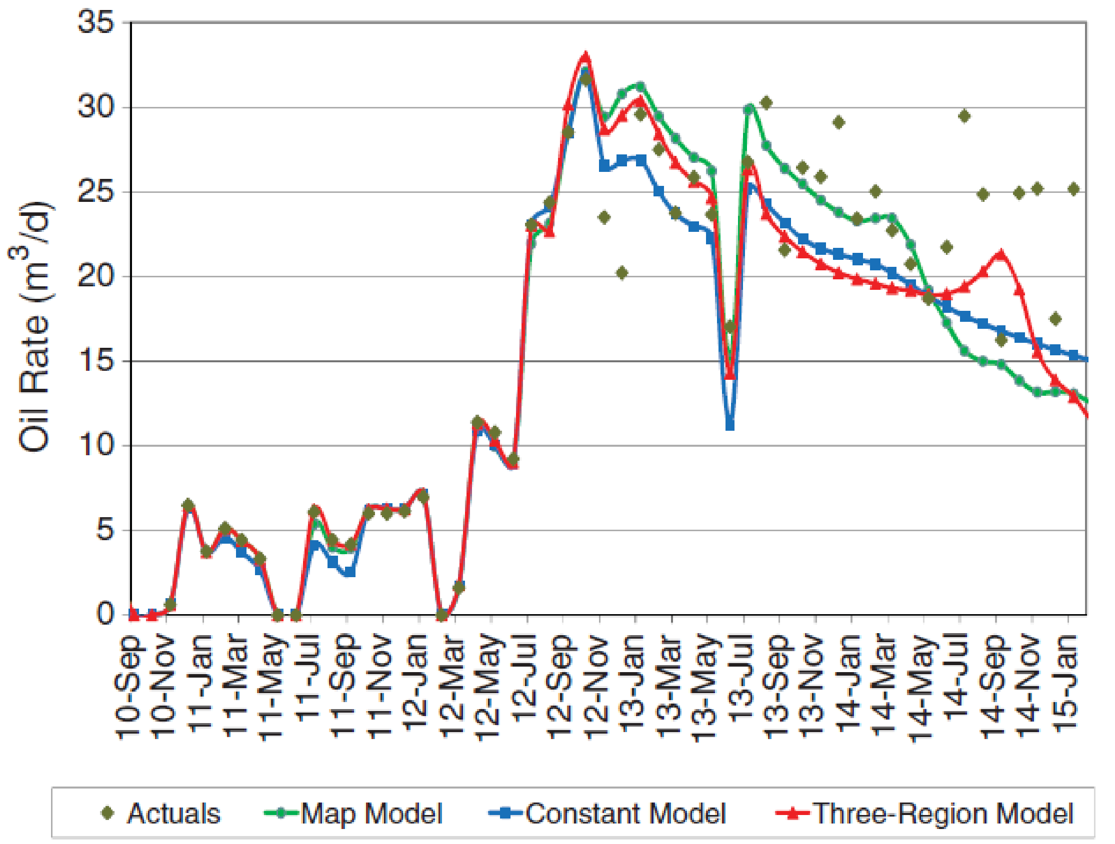

Fig. 26—Oil-production forecasts.

- History match until Oct. 2012
  - Oil rate constrained: Start to Aug. 2012
  - Production BHP constraint (blind test): Aug. to Oct. 2012
- Forecast since Nov. 2012
  - Updated injection/downtime: Oct. 2013
- Models were used to optimize pilot operation and maximize learnings (forward blind test)
  - Increase circulation temperature from 100 °C to 180 °C in July 2013
- Heterogeneous oil viscosity models provide better representation and more accurate forecasts

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After SPE-174491-PA

Water & Polymer Injection in the Pelican Lake Field (Alberta)

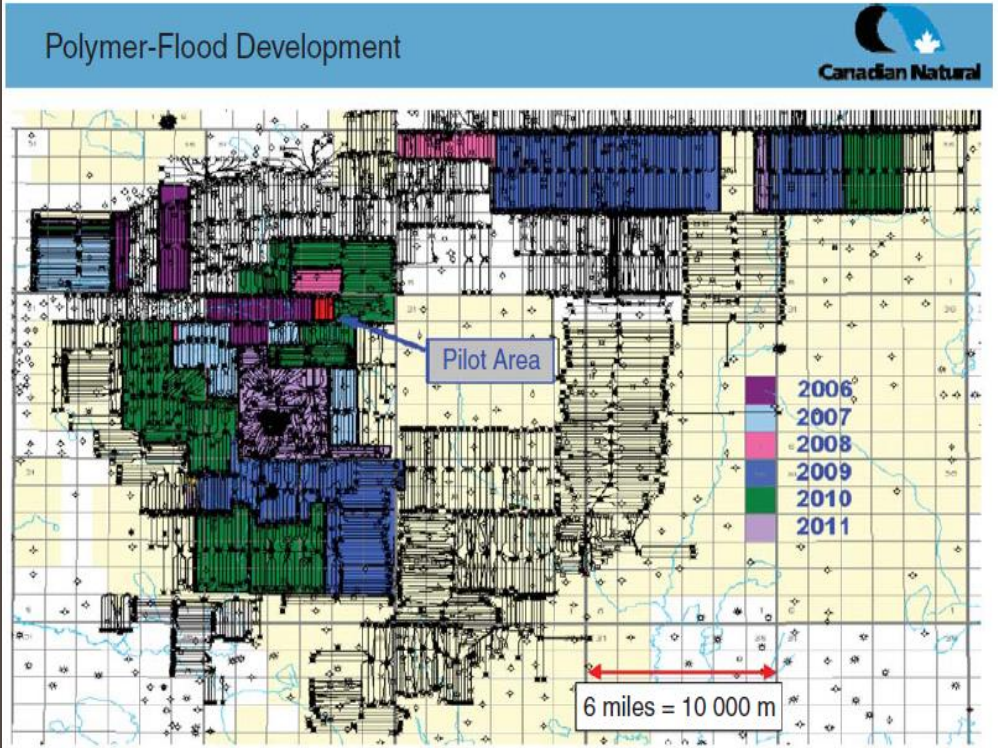

Fig. 25—Polymer-flood development on CNRL lands.

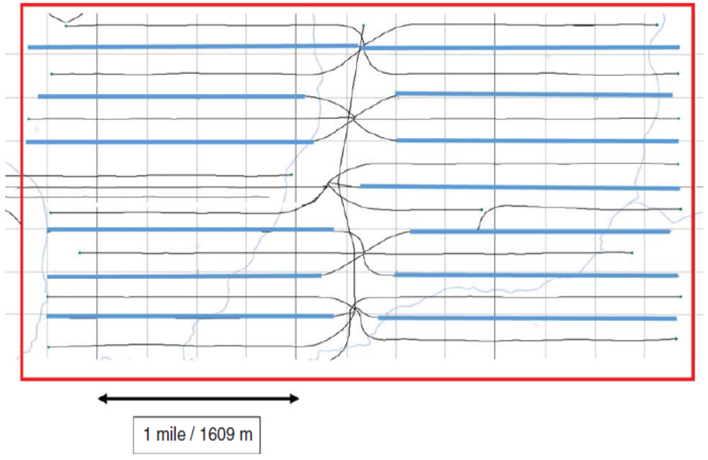

Fig. 9—CNRL North Horsetail waterflood-pilot map (injection wells in blue).

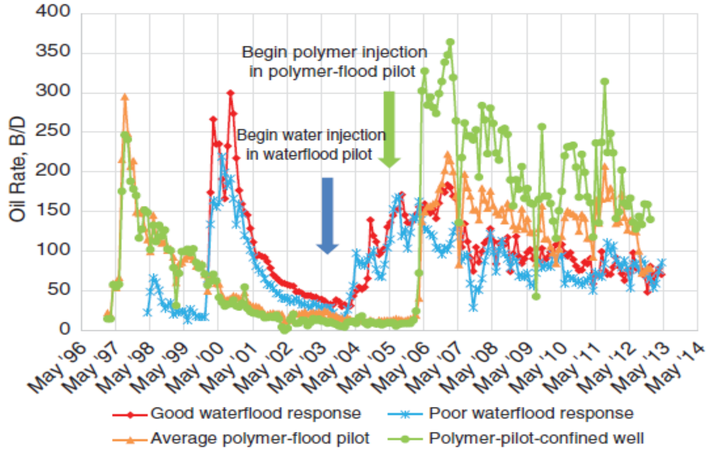

Fig. 23—Comparison of oil rate in CNRL waterflood and polymer-flood pilots.

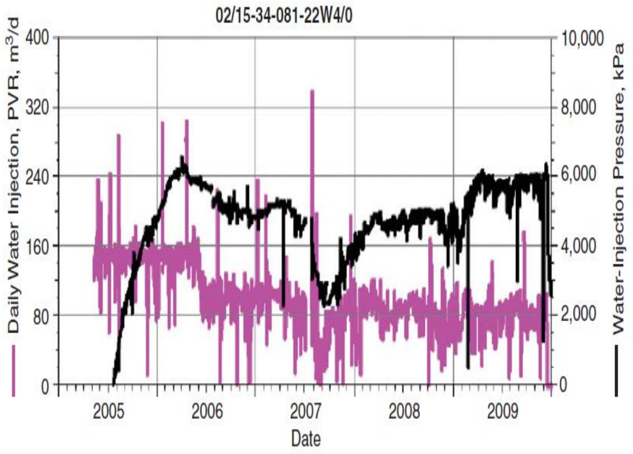

Fig. 19—Injection rate and pressure for one of the two polymer-injection wells in HTLP 6 (from CNRL 2010).

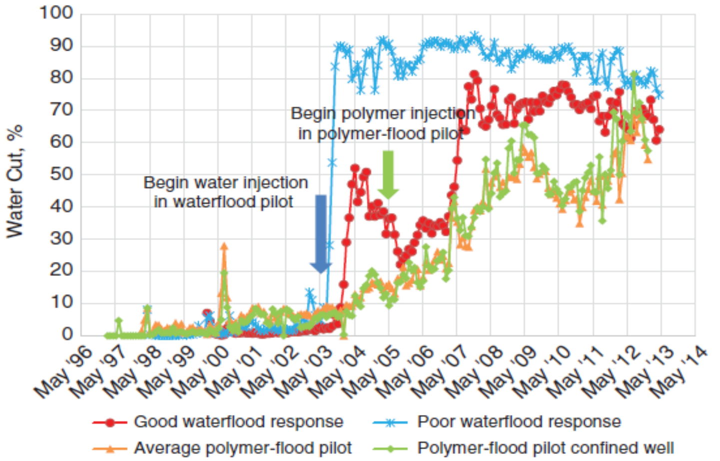

Fig. 24—Comparison of water cut in CNRL waterflood and polymer-flood pilots.

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After SPE-165234-PA

Reservoir Simulation Challenges & Opportunities

- Challenges in a few pads
  - Wellhead injection pressure increasing more rapidly than originally forecasted by reservoir simulations
  - Liquid production lower than forecasted by reservoir simulations

- Opportunities
  - Long production/injection history
  - Availability of laboratory data (water compatibility, corefloods, polymer adsorption, polymer rheology, etc.)

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What is Happening in the Field? Why is the Model not Working?

- Different hypotheses
  - Incorrect petrophysical and/or SCAL assumptions
  - Formation damage (e.g. clay swelling, polymer degradation)
  - Reservoir dilation (i.e. geomechanical effects)

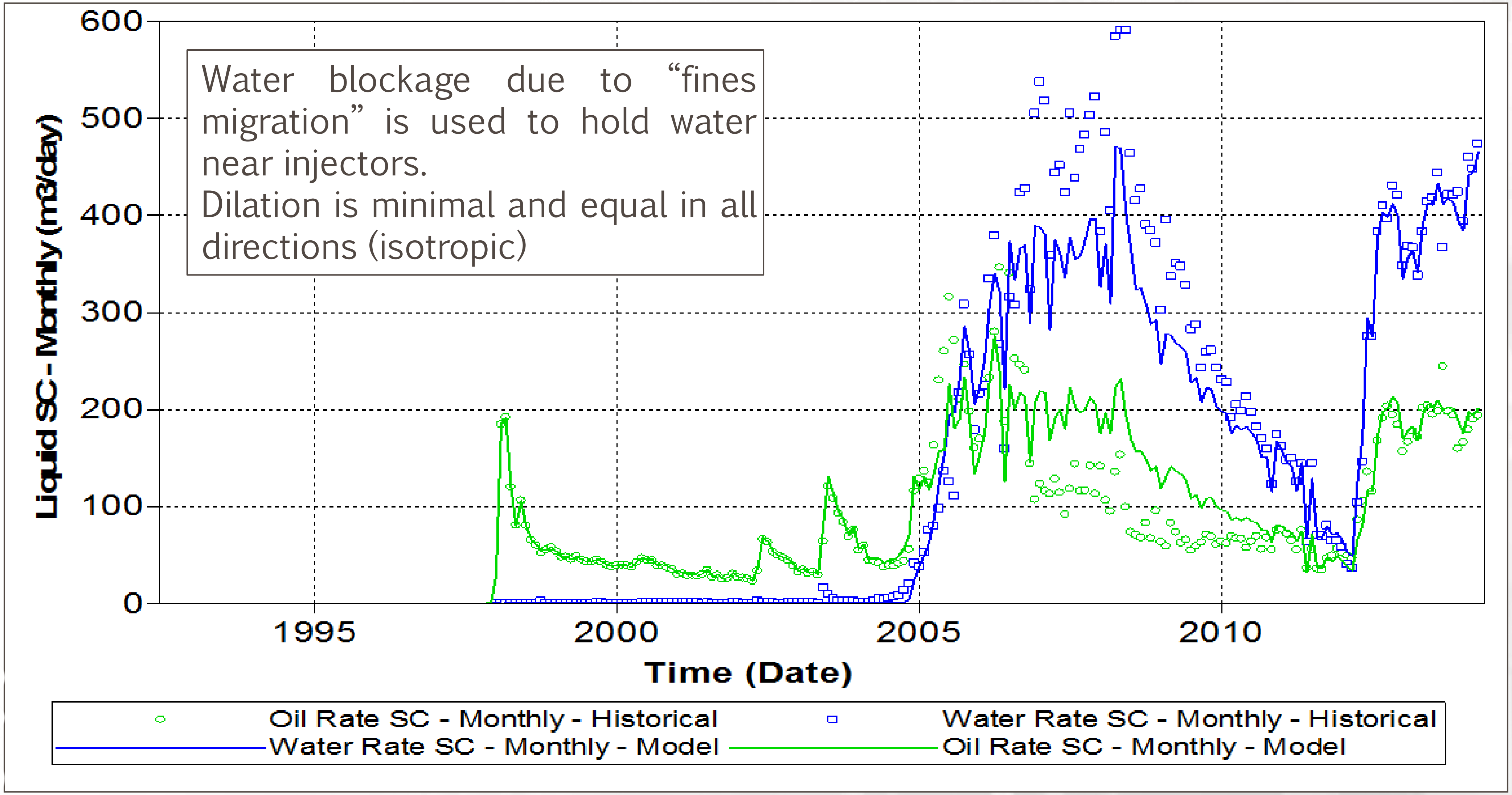
- Unsuccessful to resolve using a “conventional” simulation approach. A “different” approach was attempted
  - What do I need to do to the model to replicate the observed behaviors?
  - Try to identify possible causes by history matching different scenarios
  - Is any of the scenarios physically sound? What is the field trying to tell us?
  - Test hypothesis by performing blind tests

Further Observations

- Anomalous behaviors were not necessarily exclusive to the polymer injection phase
  - Challenge was magnified during polymer injection
  - Need to re-visit plausible causes

- Some of the scenarios considered
  - Formation damage due to “fines migration” based on CMG’s model
  - Reservoir dilation and increase of reservoir pore volume
  - A combination of the above two mechanisms

Scenario 1 – Fines Migration Only



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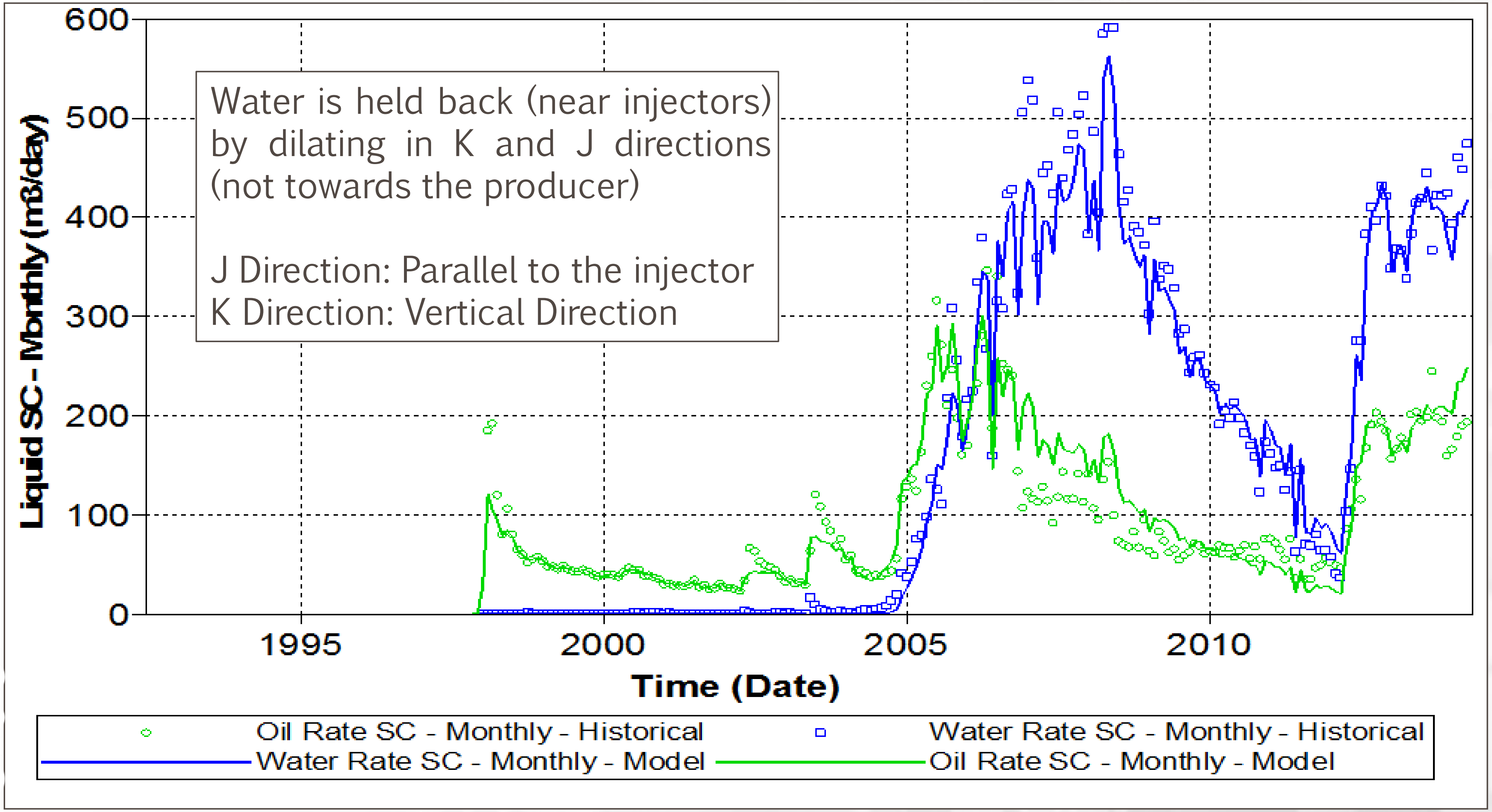
Scenario 2 – Reservoir Dilation



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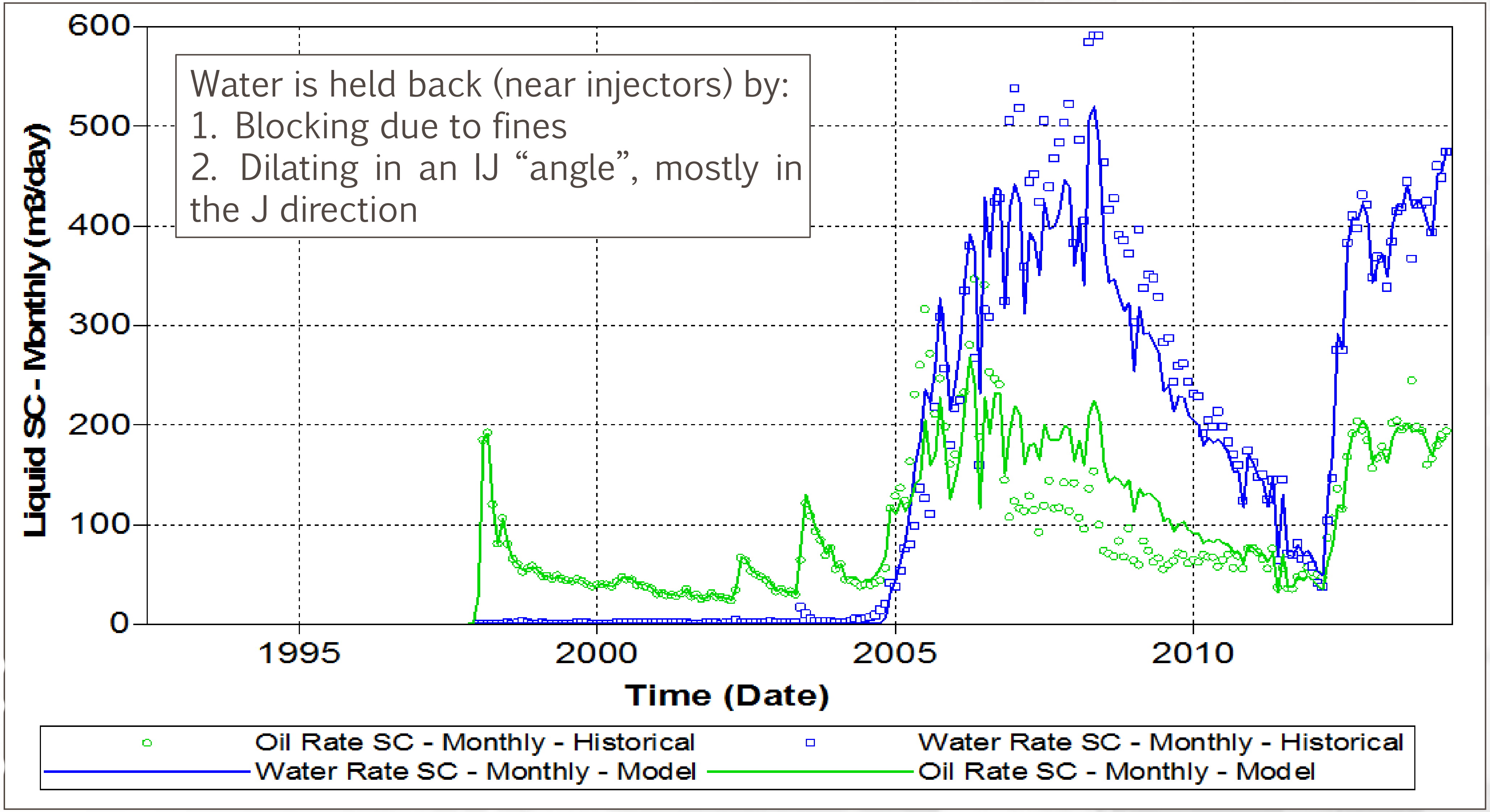
Scenario 3 – Combination of the Two Mechanisms



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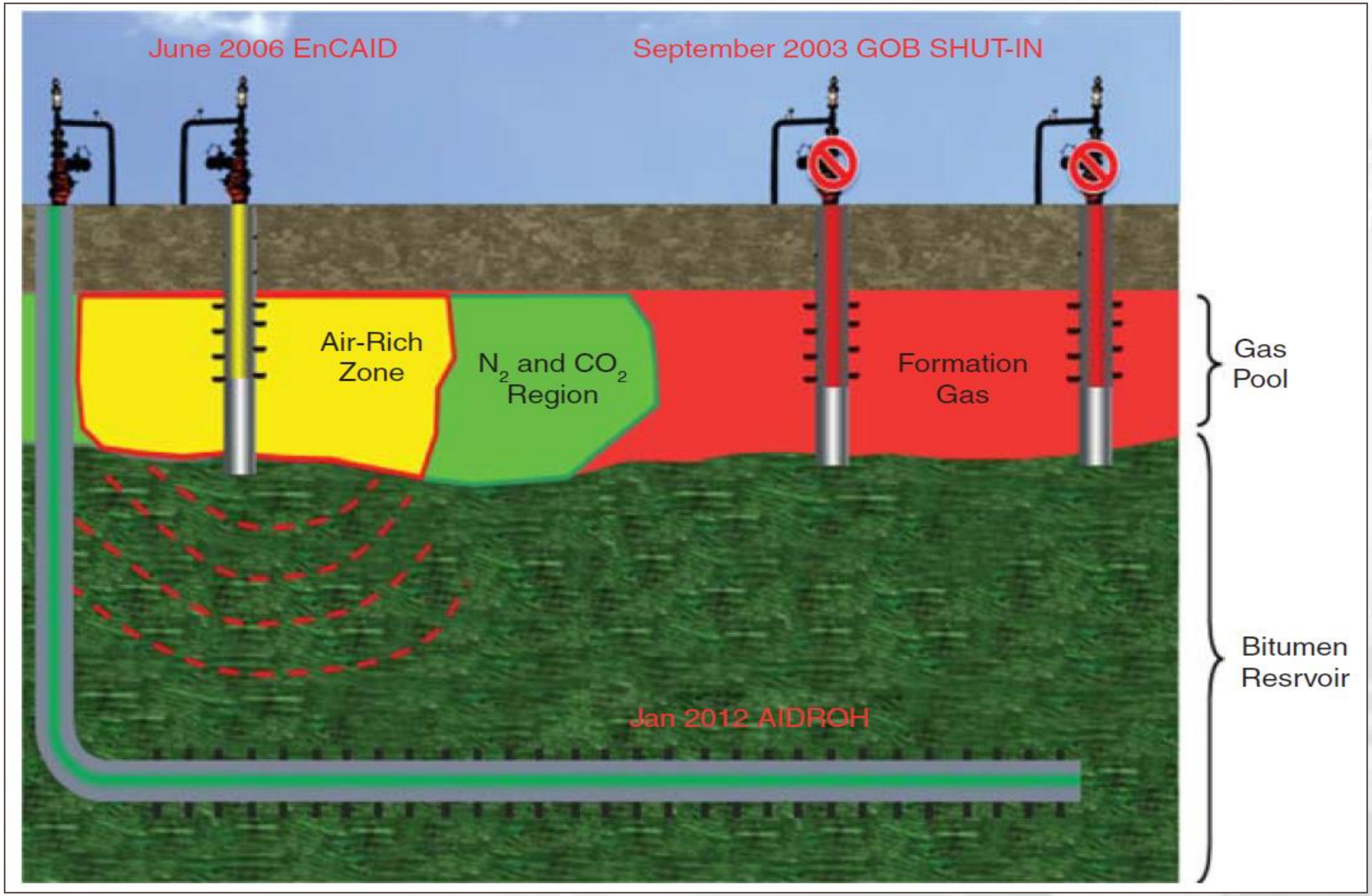
Further Analyses and Comments

- All 3 scenarios seemed possible. However:
  - A blind test in the model can assist in identifying most plausible one
  - Testing of model in other pads can assist in confirming the main mechanisms or identifying differences in different pads

- Well tests can be designed to test hypotheses, and further understand reservoir behavior

- Additional laboratory work can be performed to identify source of the problem in specific pads

In-Situ Combustion Pilot – Process Overview (EnCAID & AIDROH)



After SPE-174455-PA

Reservoir Properties & Site Layout

Formation	Wabiskaw
Depth	465 m
Thickness	25-30 m
Porosity – Average	35%
Oil Saturation - Average	65%
Permeability - Average	1,350 mD
Oil Viscosity @ 13 °C	~35,000 cP

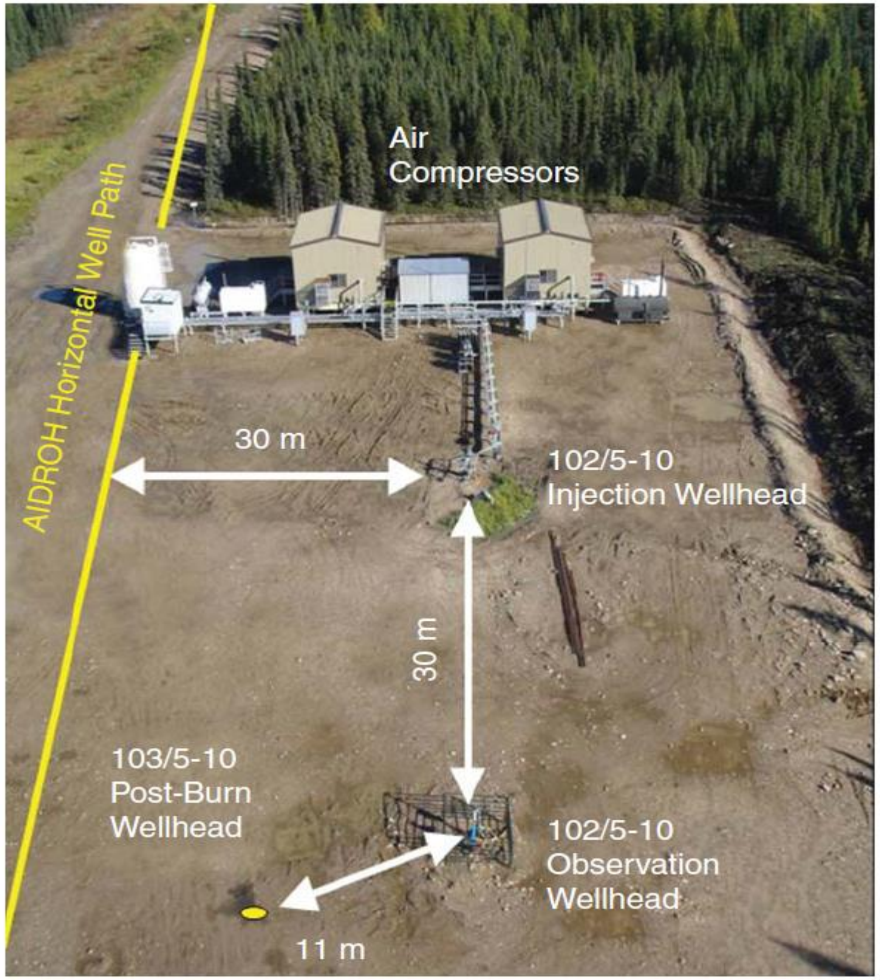


Fig. 3—AIDROH-pilot well layout.

After SPE-174455-PA

Temperature Profiles in Observation and Production Wells

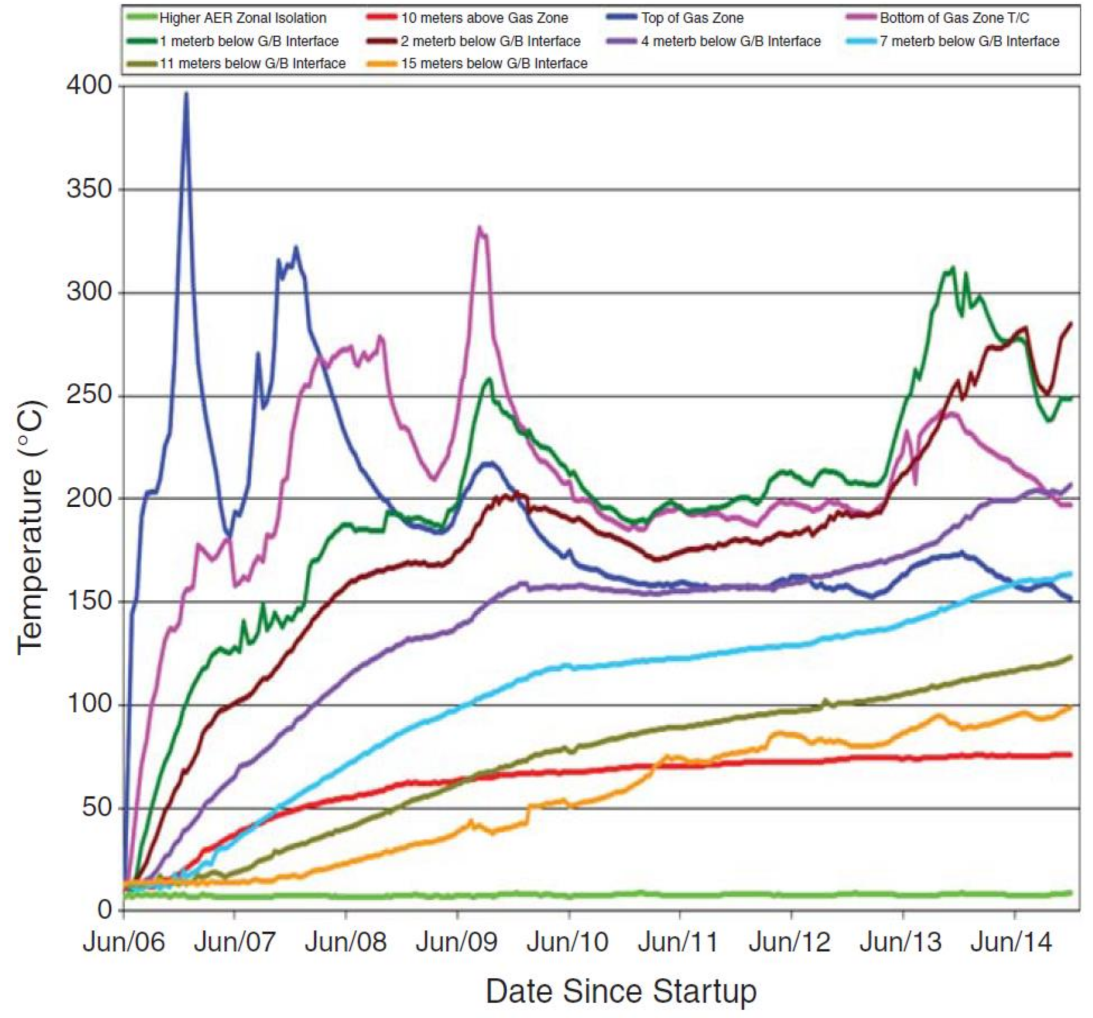


Fig. 4—Observation-well temperatures with time.

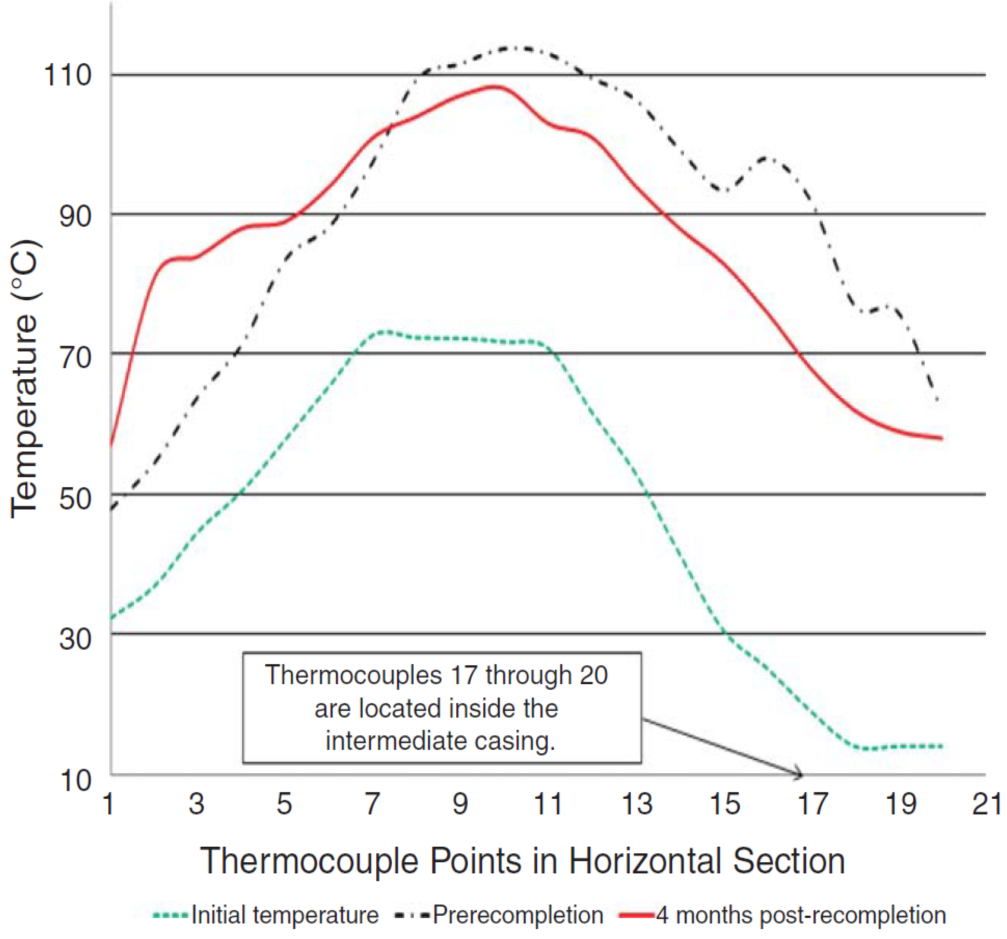


Fig. 8—Temperature along the AIDROH well at various times.

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Reservoir Simulation Challenges & Opportunities

- Challenges
  - Unexpected temperature behavior in gas cap
    - Two temperature peaks
    - Tilted combustion front
    - Different shapes of temperature peaks
    - Unexplained by laboratory experiments
  - Complex process (chemical reactions, etc.)
  - It requires a fine simulation grid
  - Long simulation run times
- Opportunities
  - Successful ignition and combustion performance
  - Outstanding surveillance data
  - Heating of oil zone was mostly through thermal conduction (simpler process)

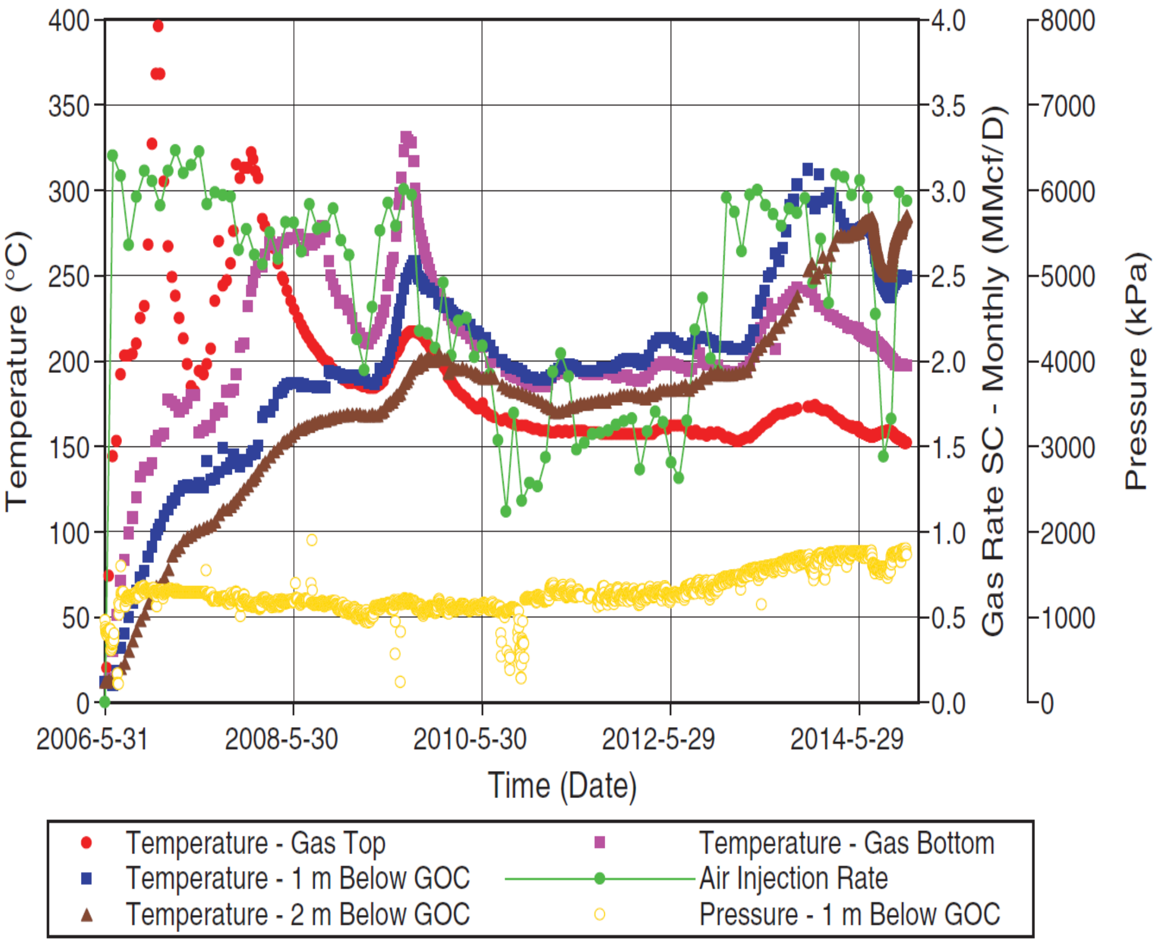

Fig. 16—Observation-well pressure and temperatures at the top of the reservoir.

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Temperature History Match – Heater Model

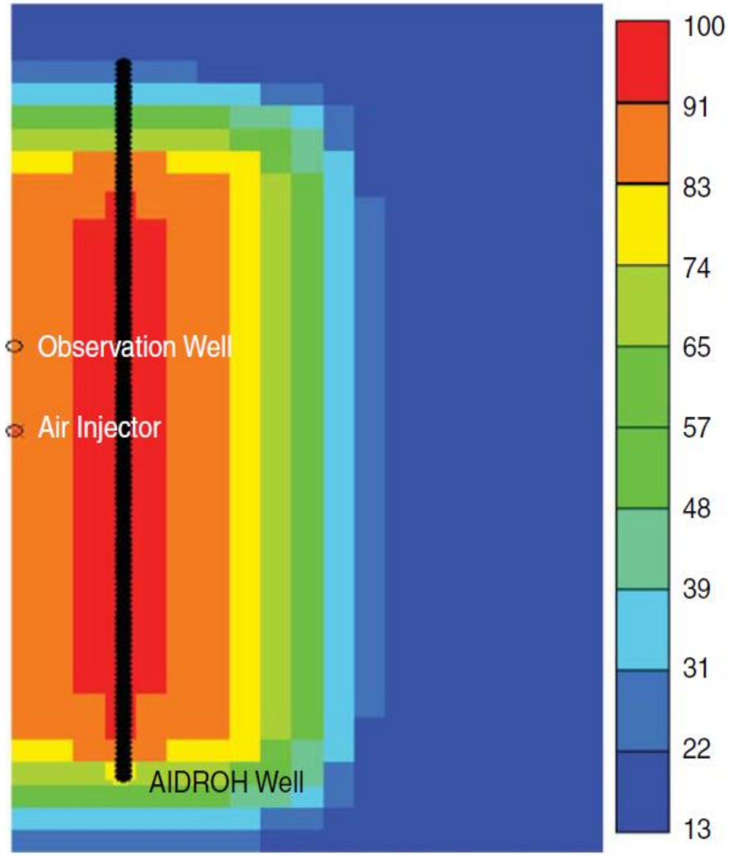

Fig. 18—Simulated temperature (°C) at 15 m into the bitumen at the end of 2014—heater model.

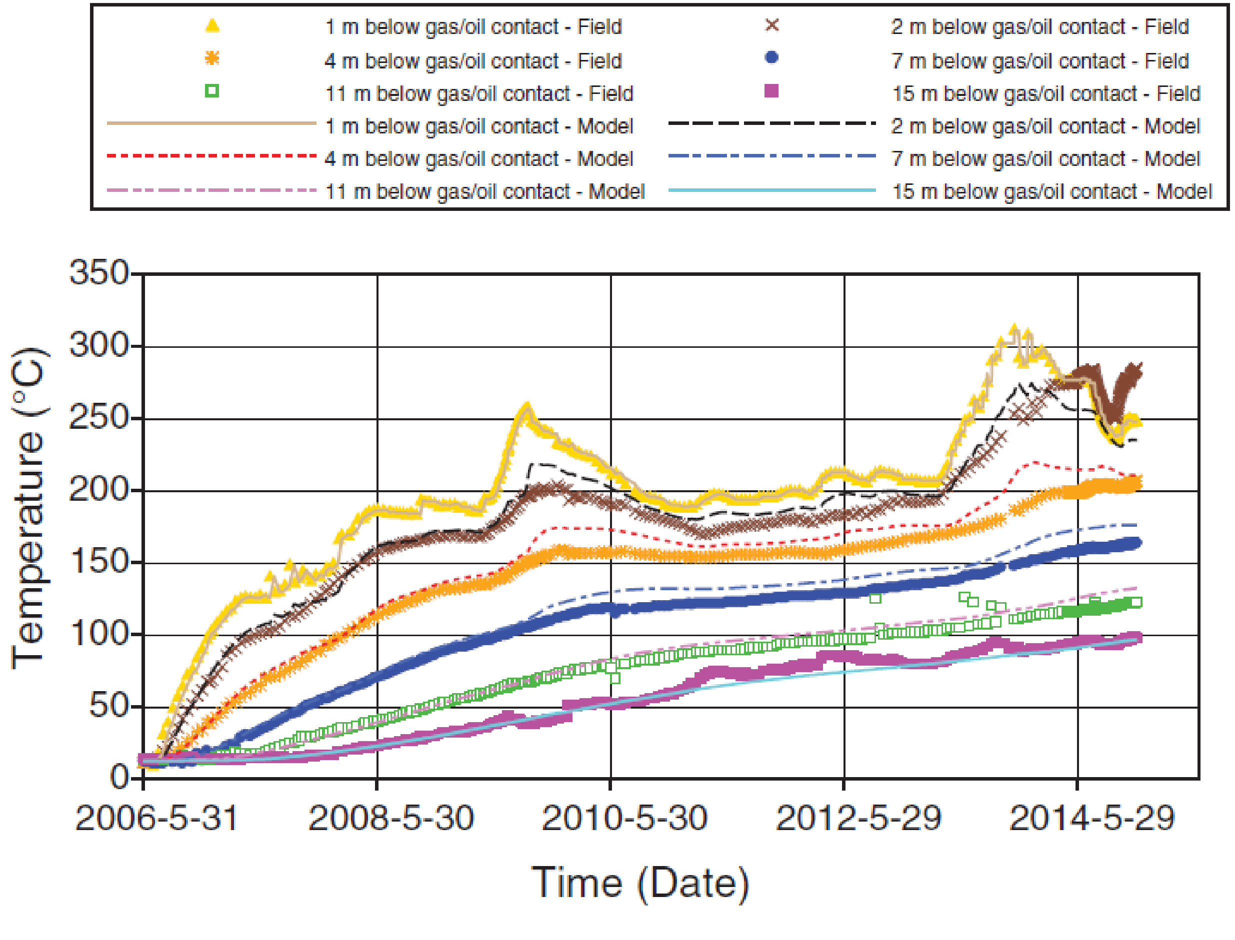

Fig. 17—Simulated temperature in the observation well—heater model.

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Simulation History Match & Production Forecast – Single Reaction Model

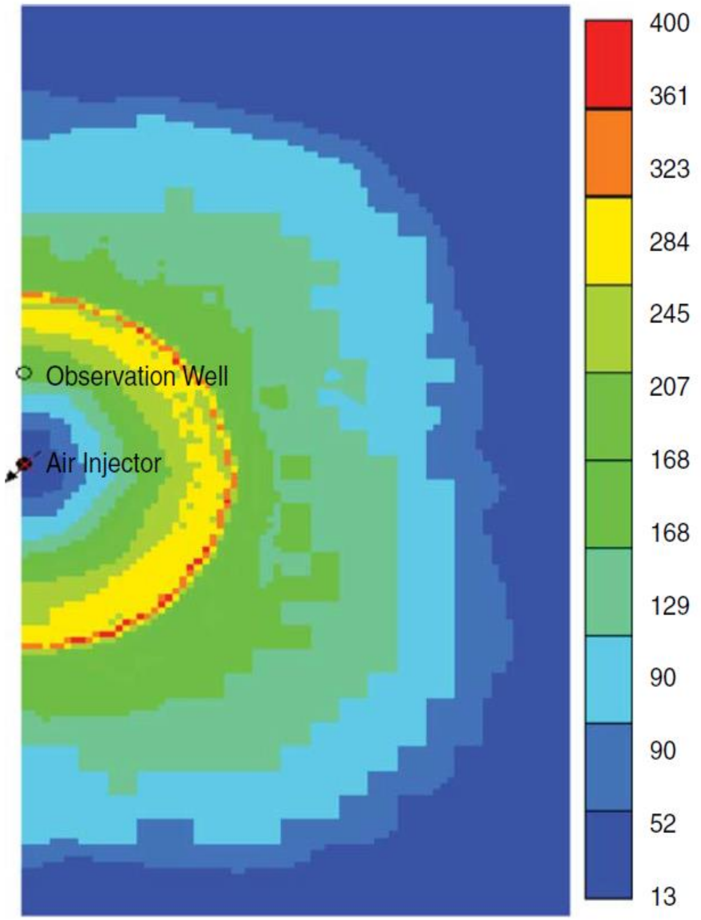

Fig. 20—Simulated temperature (°C) 1 m into the bitumen at the end of 2014—in-situ-combustion model.

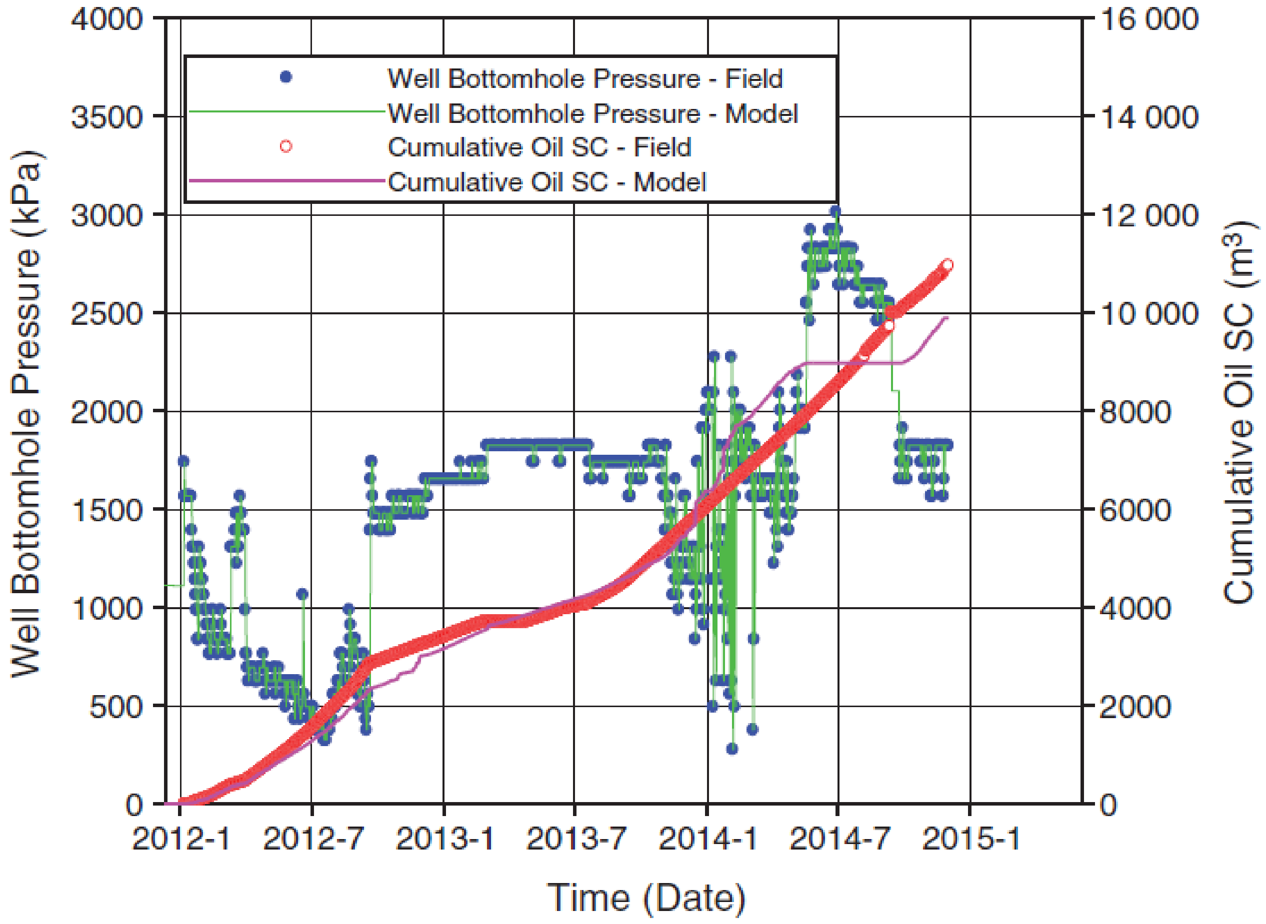

Fig. 19—Simulated oil-production performance—in-situ-combustion model.

After SPE-174455-PA

Conclusions

- Analyzing the raw data to understand project performance by "listening to the field", proved to be key to improving the predictability of reservoir simulation models
- Surveillance and monitoring of EOR pilot projects is of extreme importance to their success and need to be designed and analyzed carefully
  - Laboratory data is important but let's remember to listen to the field
- Remember to blind-test your models (i.e. "Forecast" known results)
- Run pilot as a "controlled" experiment (i.e. forward blind testing)
  - Use model to design experiment and compare forecast with actual results
- This exercise is made simpler by the use of current simulation technology (assisted history matching, parallel computing, faster hardware, etc.), which allows us to evaluate/run multiple scenarios and perform multiple sensitivities, relatively easily

Acknowledgements

- Past and current operators of the fields and their publications on the pilots and projects discussed

- Thank You – Questions?

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