Cross-well EM: Technology for reservoir monitoring, image and characterization

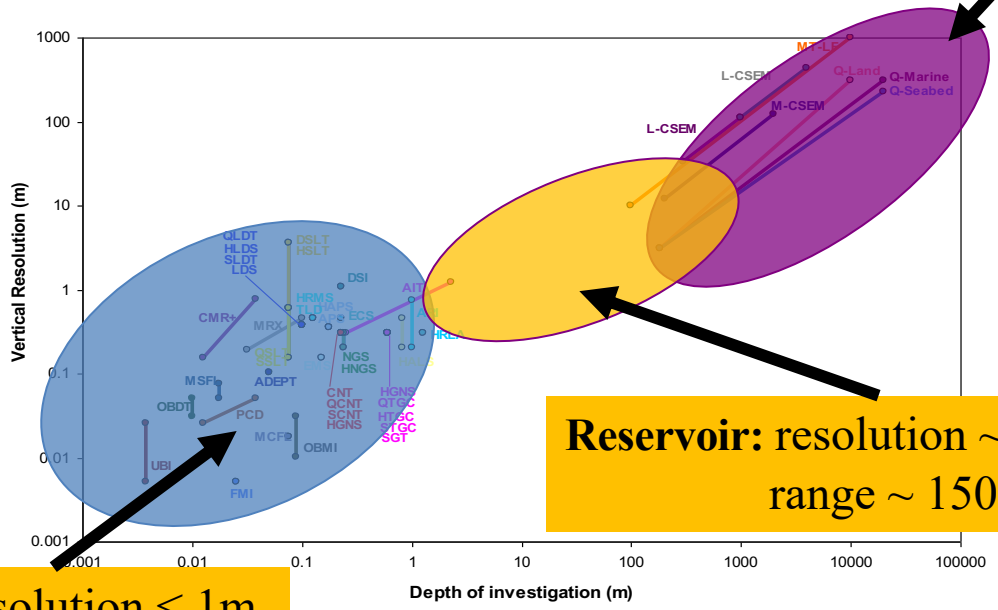
Ping Zhang

Agenda

- Introduction
- Cross-Well EM Technology
- Case Histories
- Conclusion

EM Survey Methods

Basin: resolution ~ 10's – 100's m
range ~ many km

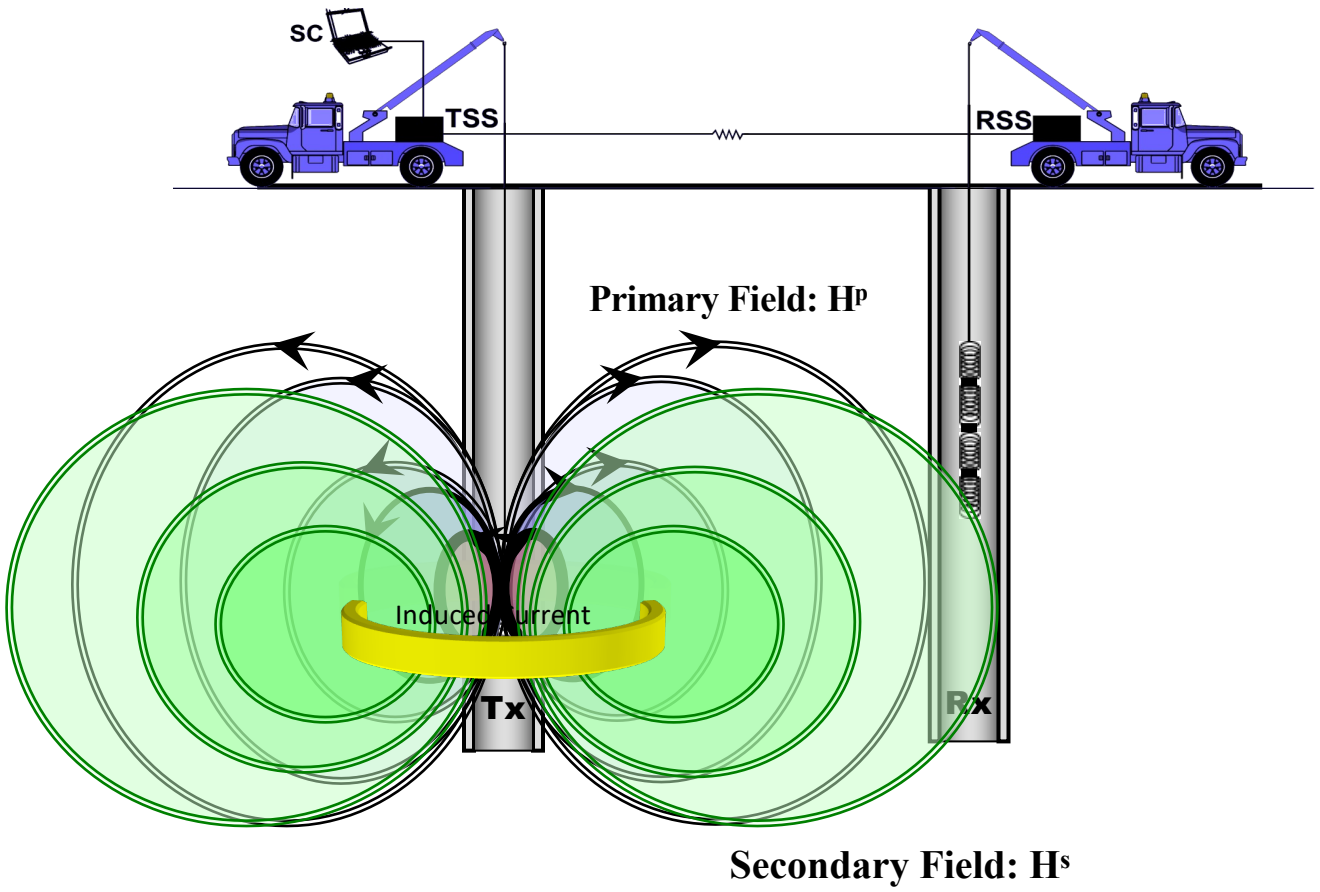


Reservoir: resolution ~ 1–5m
range ~ 1500m

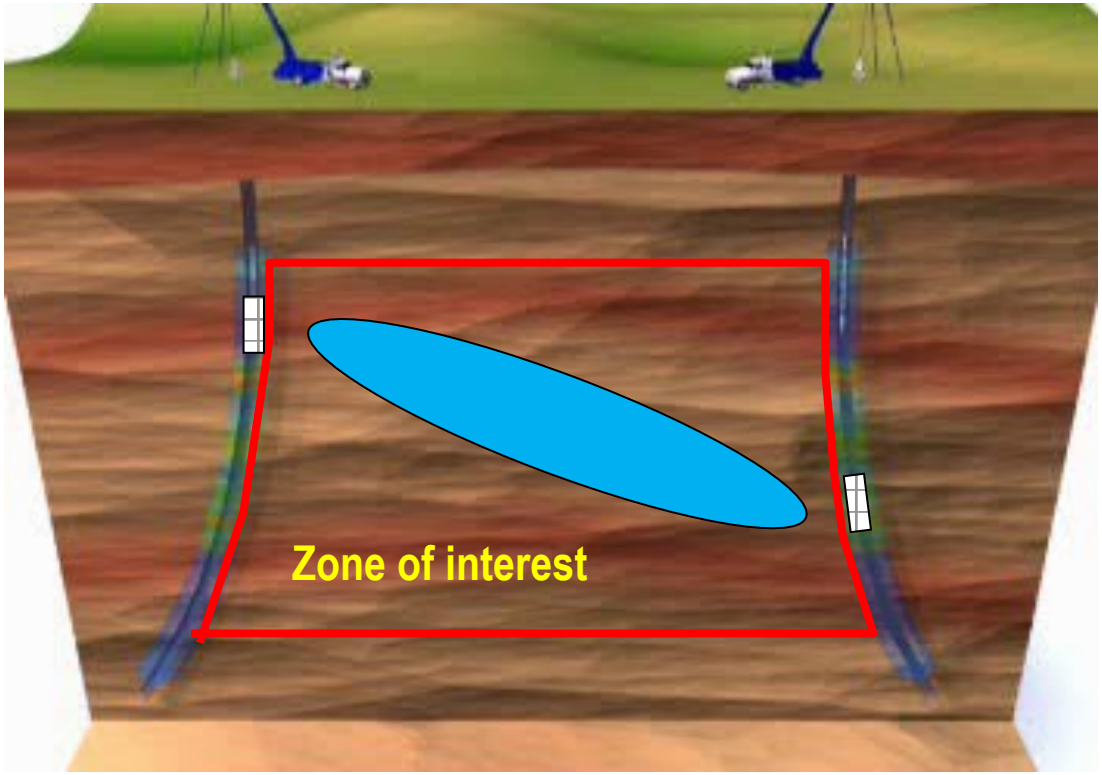
Logs: resolution < 1m
range < 1 – 2m

Cross-well EM technology

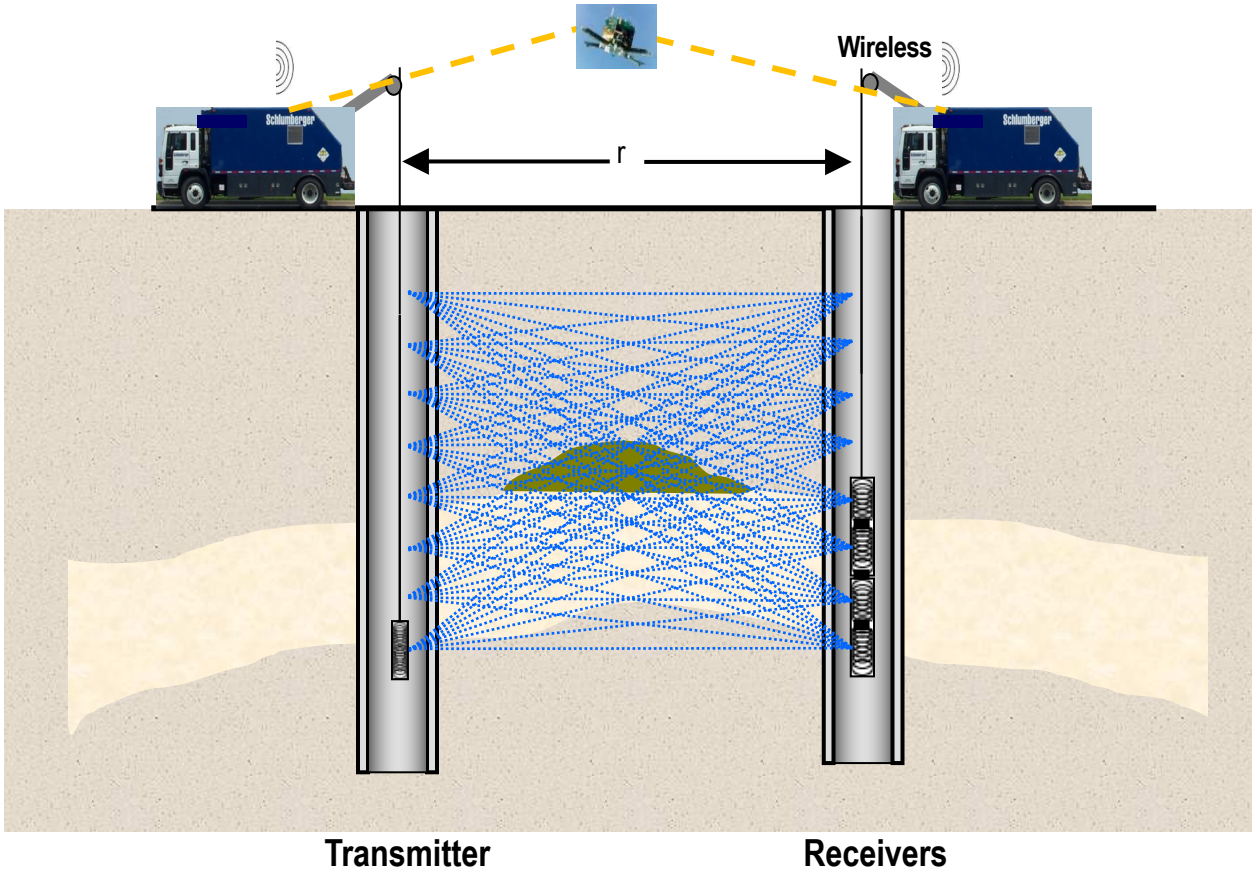
The Measurement Principle of Cross-Well EM



Inter-Well Region Interrogated by Tomography



Cross-Well EM Tomography

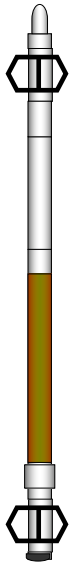


Tool Specifications

Transmitter

OD: 3 3/8“ (86mm)

Length: 9.88m



Receivers

OD: 2”1/8 (54mm)

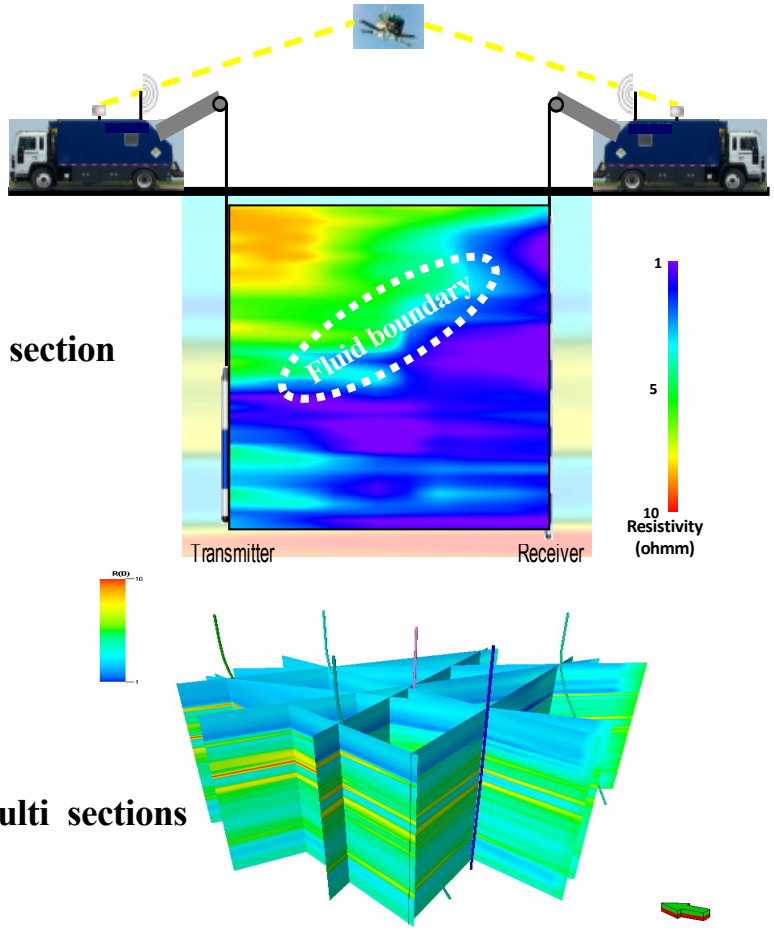
Length: 22.5m for 4 receivers

Optimized at frequencies from 10-1000 Hz

Well type and separation

Transmitter Well	Receiver Well	Max Spacing
Open	Open	1500m
Fiberglass	Fiberglass	1500m
Open	Steel casing	700m
Steel casing	Steel casing	n/a

Cross-well EM Applications



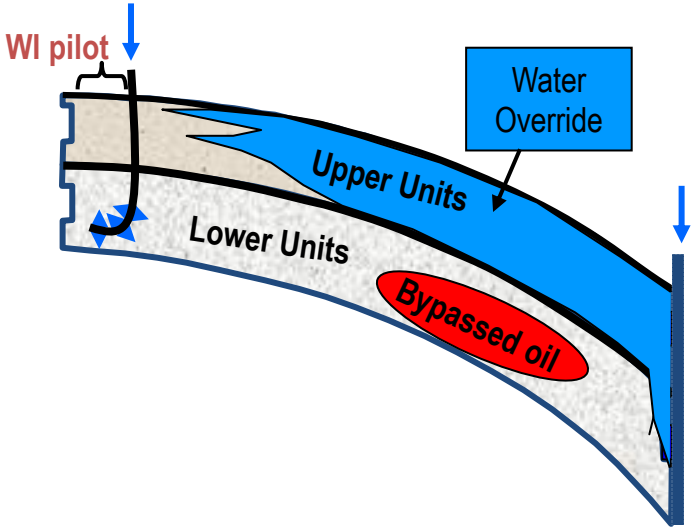
Applications

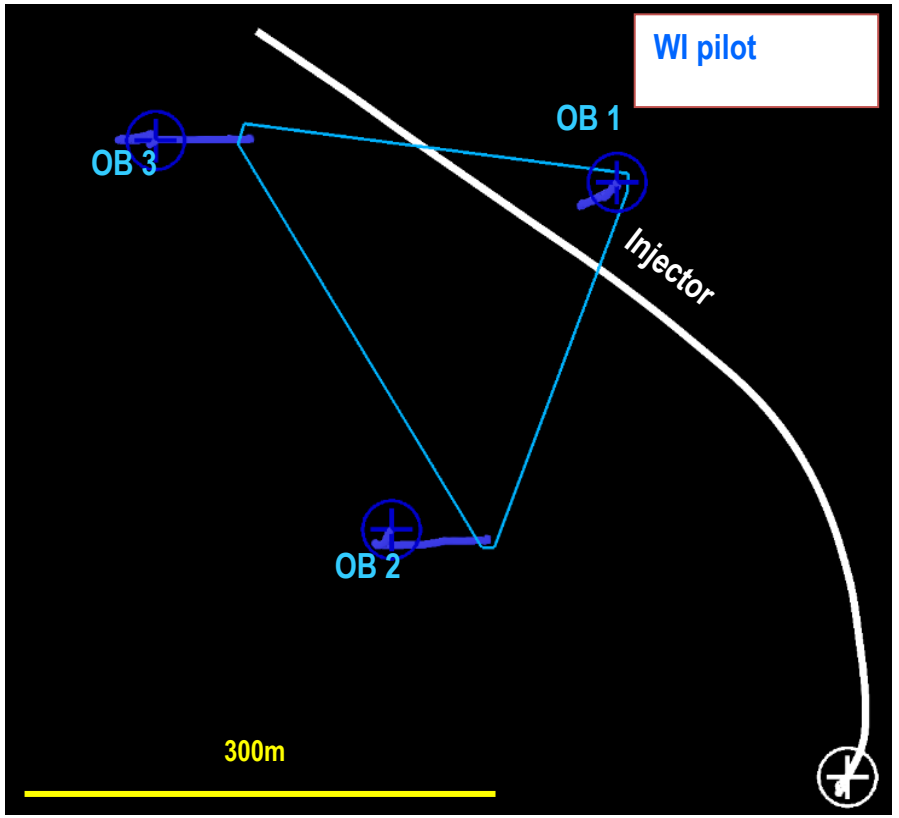
- Fluid front monitoring
- Identification of bypassed pay
- Enhanced reservoir characterisation & modelling
- Drilling optimisation

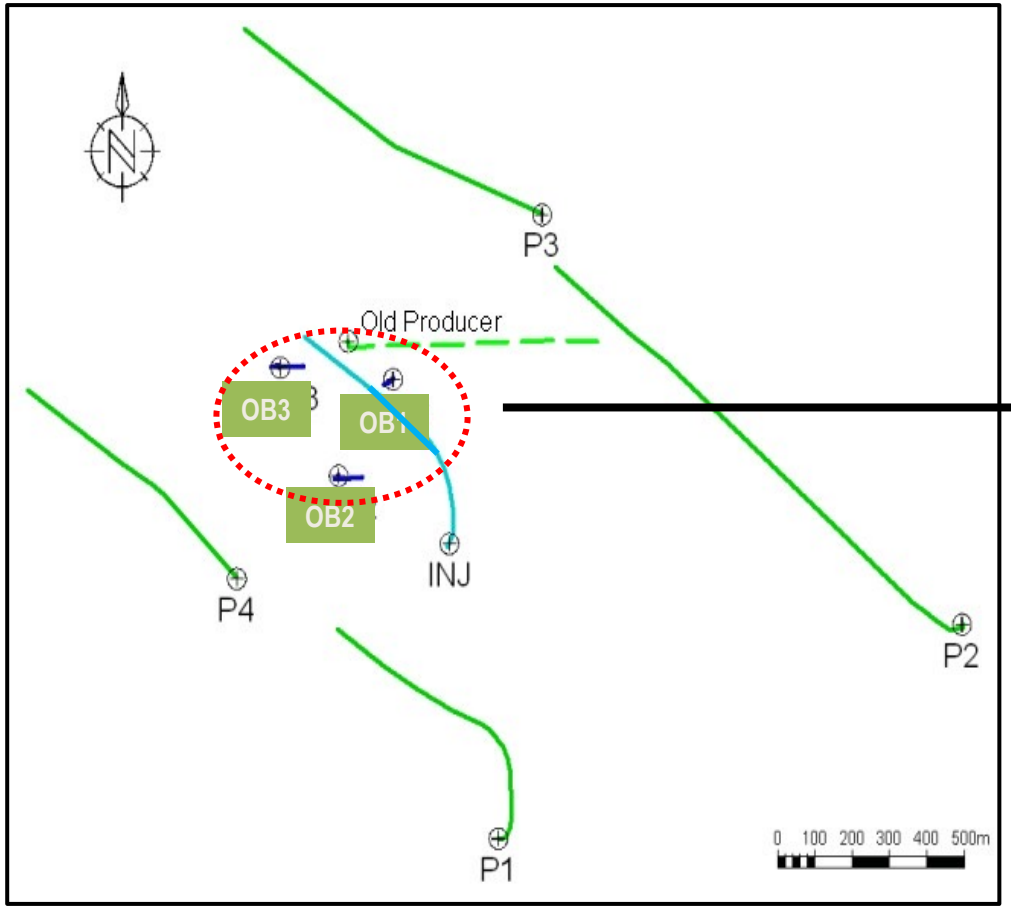
Monitoring Water Flood

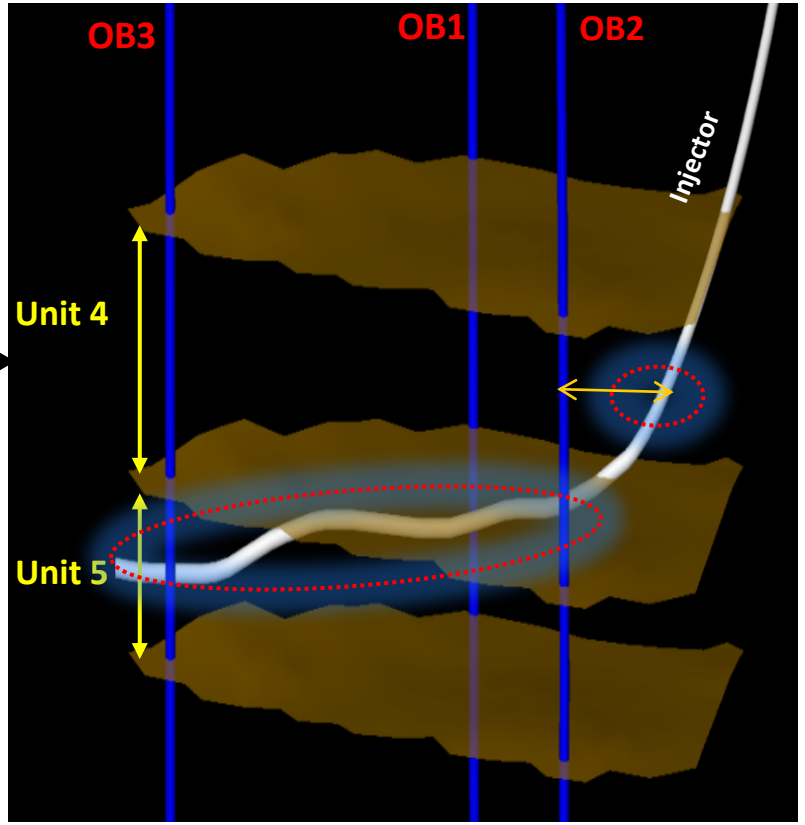
Permeability ranges from 1 md to 500 md

Peripheral water in uppermost reservoir units (high permeability)



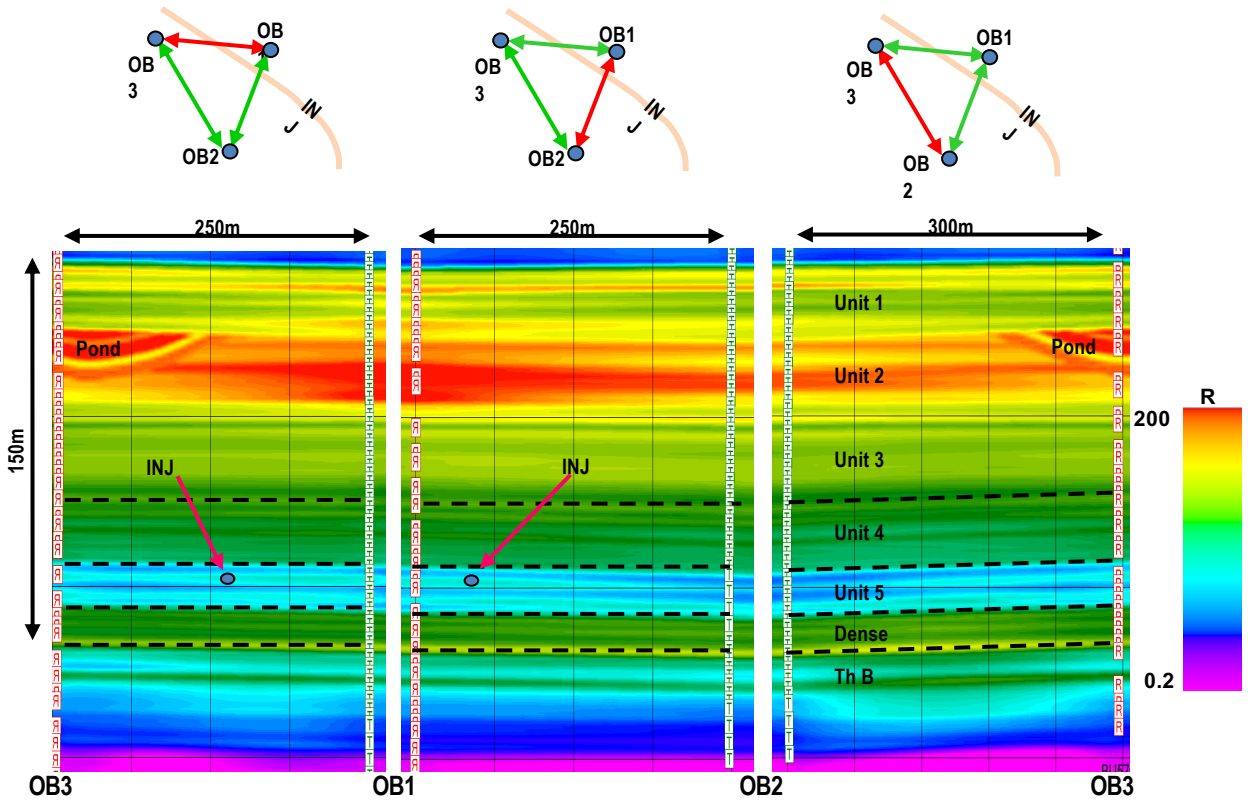




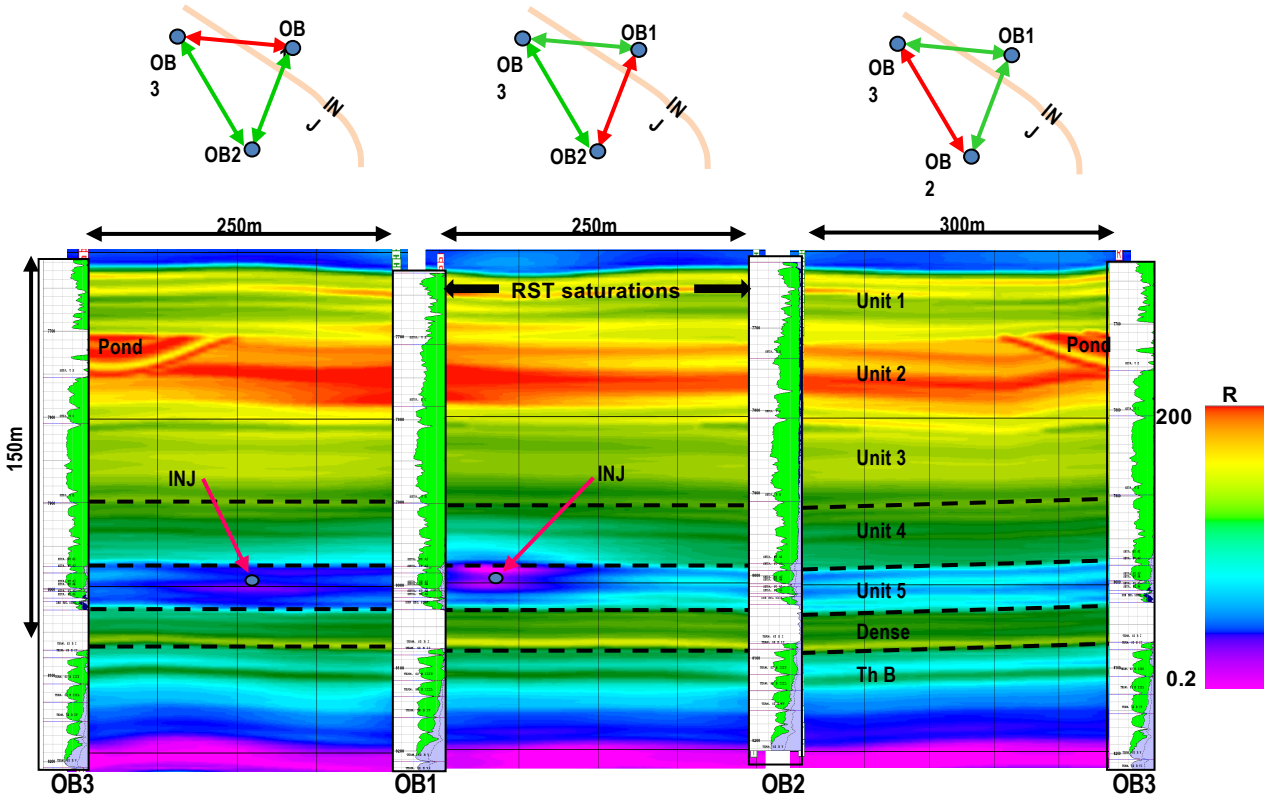


Permeability: unit 4 ~max 50md

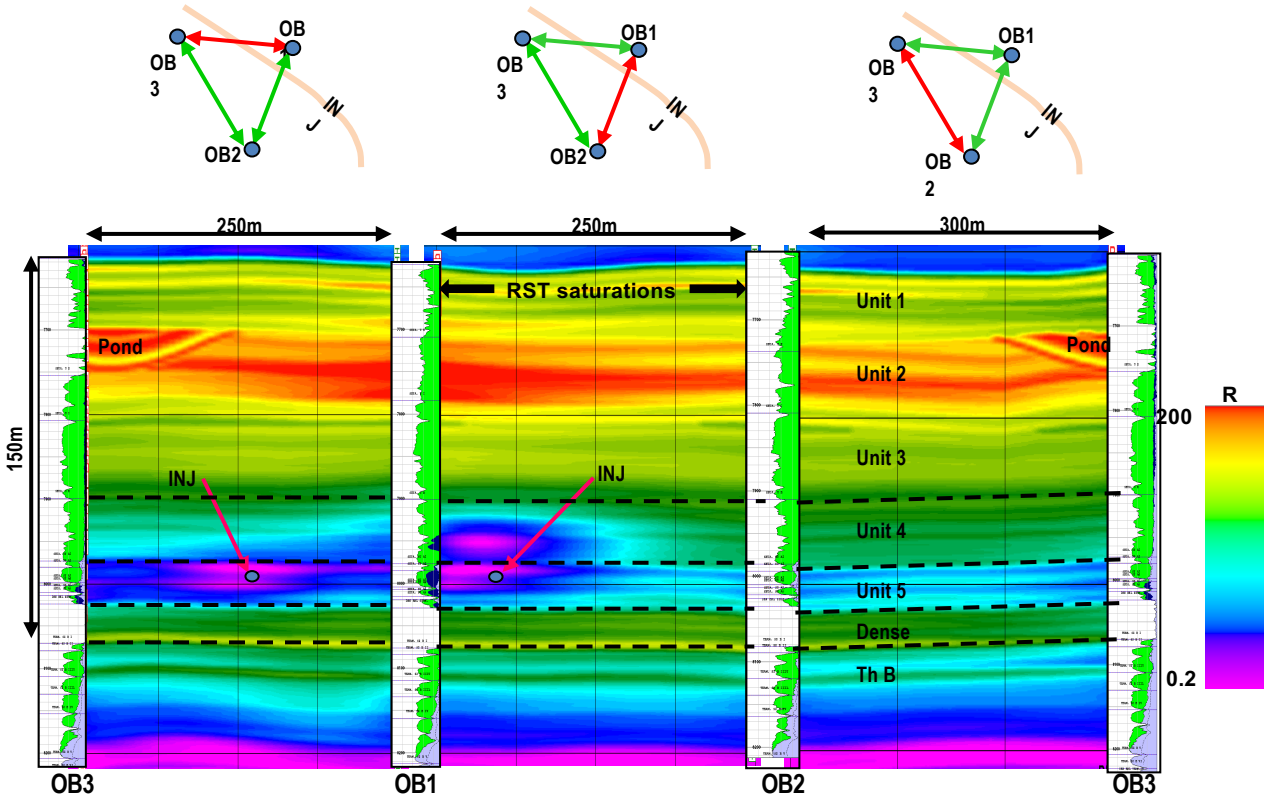
unit 5 ~max 15md



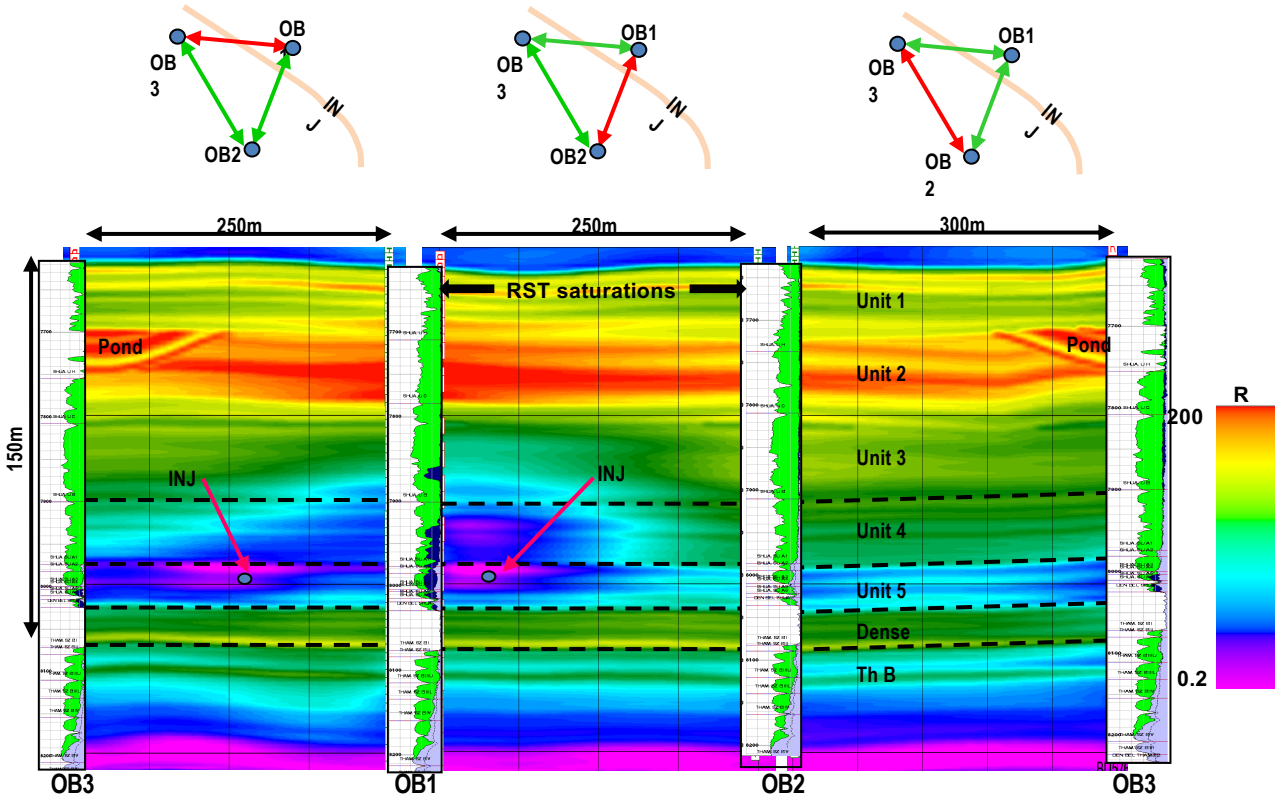
Baseline survey (September 2007, before the injection)



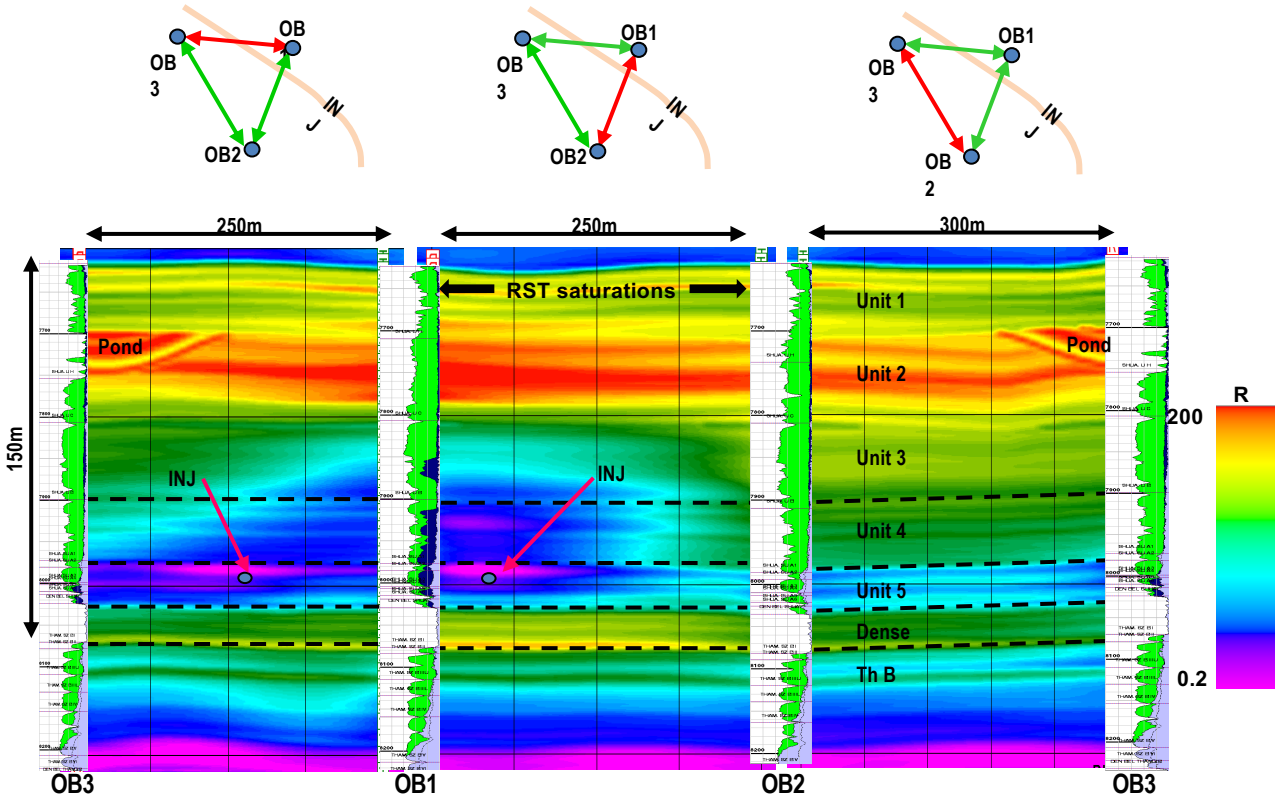
Time-lapse 1 (June 2008, after 6 months of injection)



Time-lapse 2 (December 2008, after 1 year of injection)

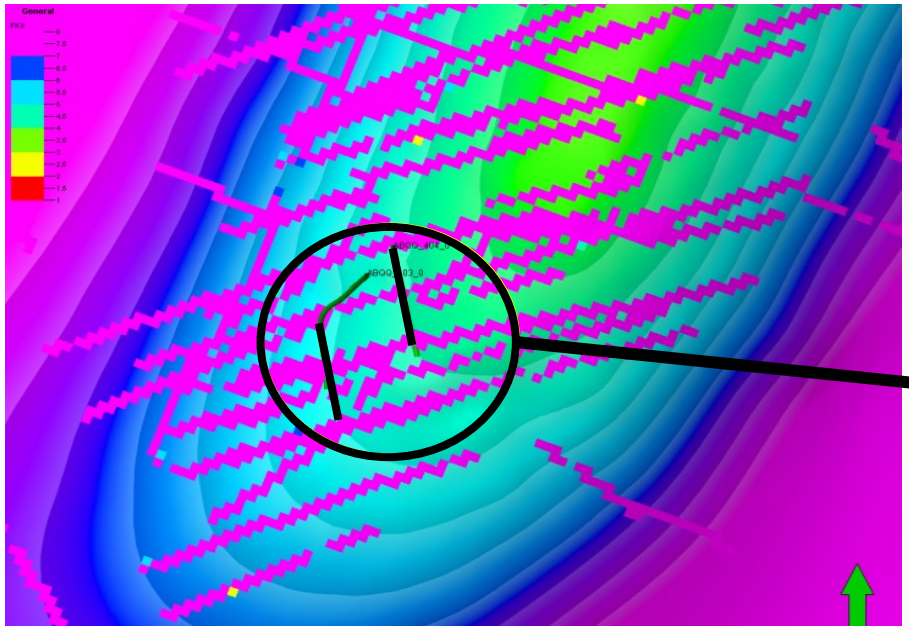


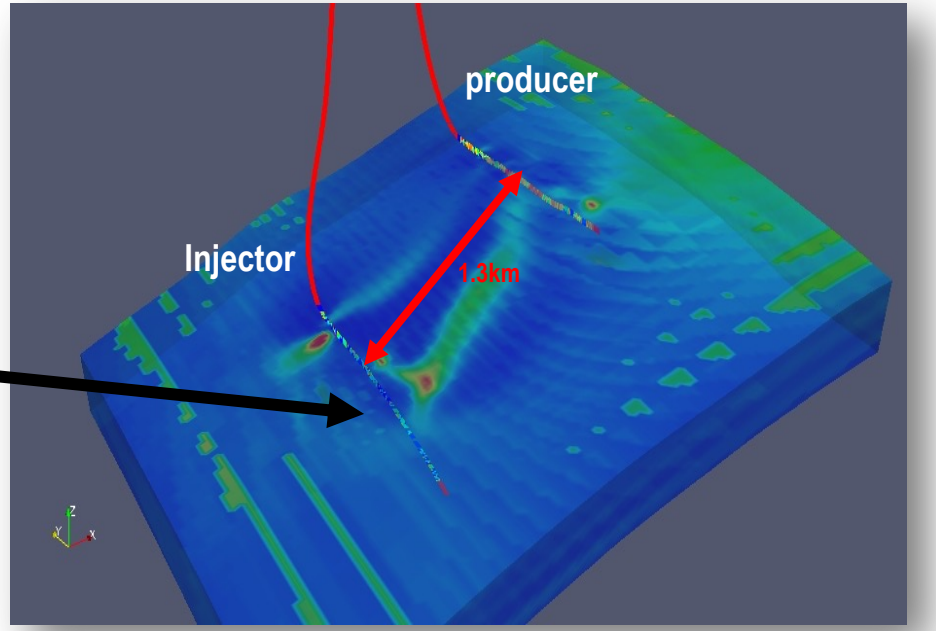
Time-lapse 3 (July 2009, after 1.5 years of injection)



Time-lapse 4 (March 2010, after 2.3 years of injection)

Defining Fracture System and Locating by-passed Hydrocarbon





Reservoir is tight and highly fractured

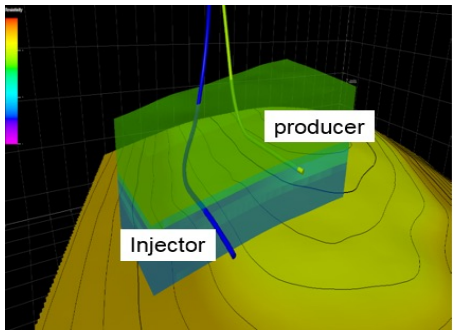
Water injection, 2000

Production shut down, 2013

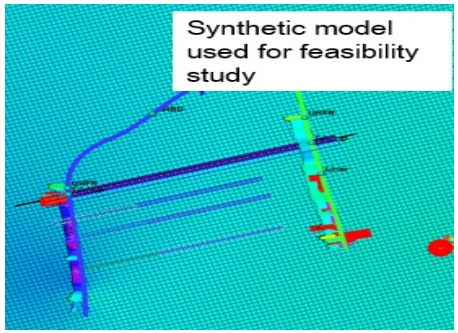
Mapping saturation distribution

Cross-well EM

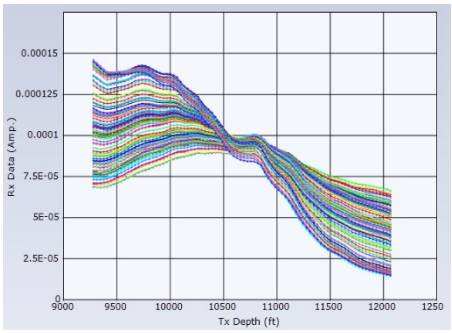
Project workflow:



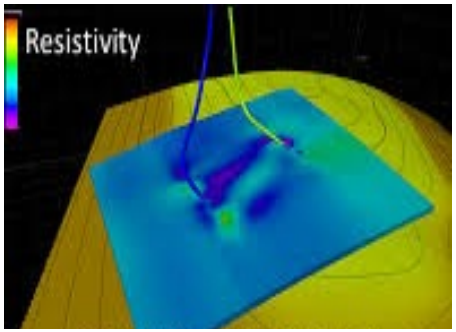
Project setup
2012



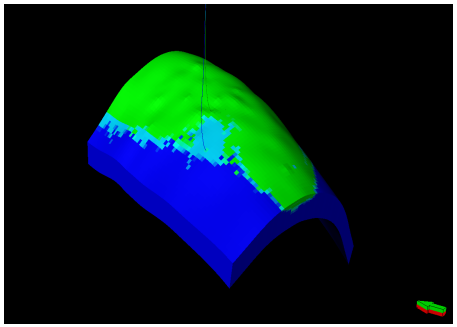
Simulation
2013



Data collection
2014

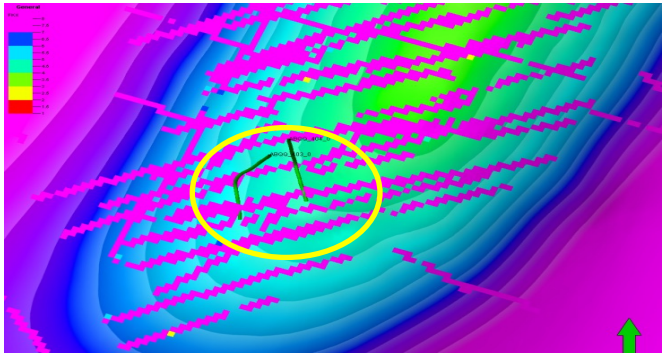


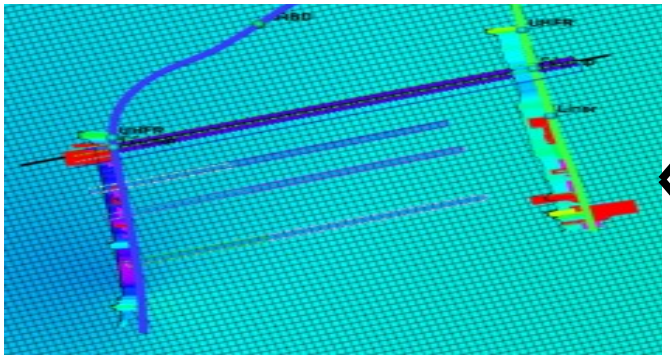
Resistivity Inversion
2015



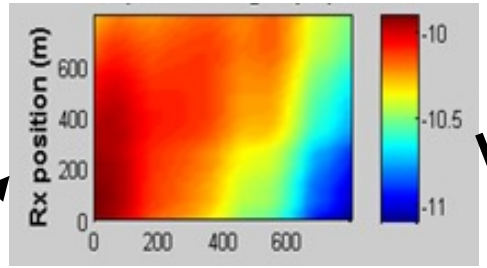
Water Saturation
Q3, 2016

Pre-survey simulation (1)

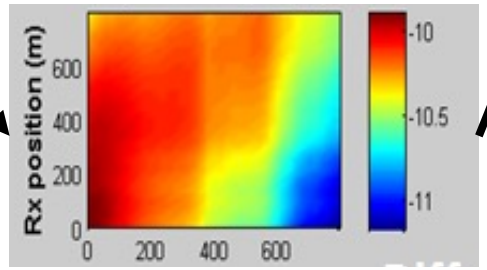




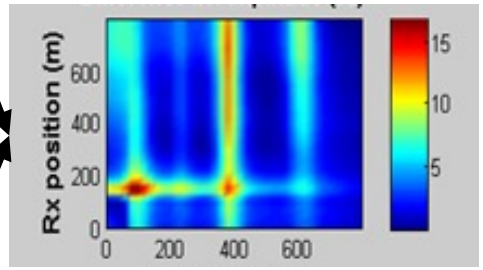
Without fractures



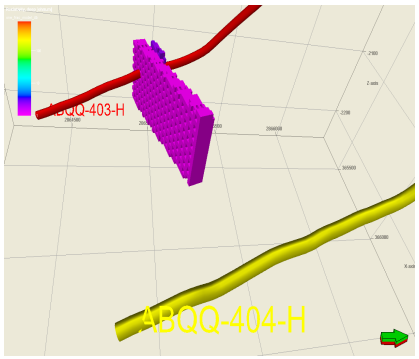
With fractures



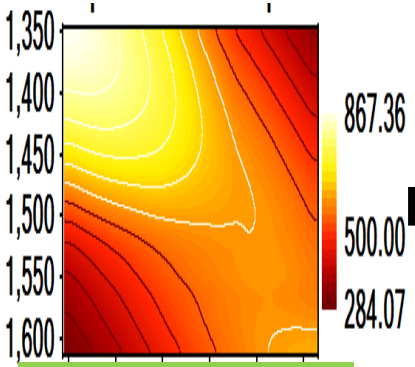
Difference



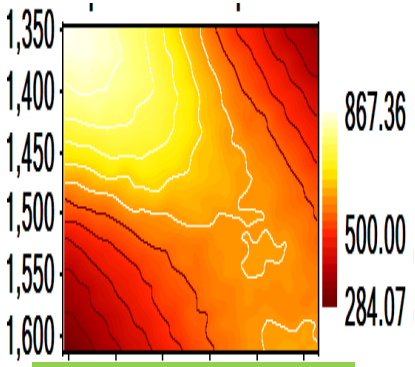
Pre-survey simulation (2)



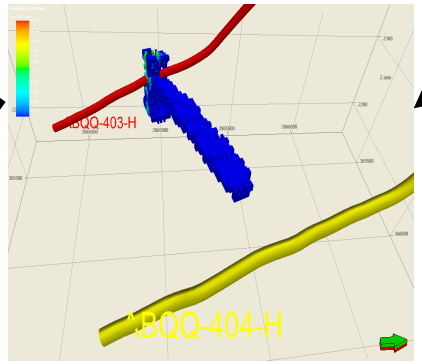
true model



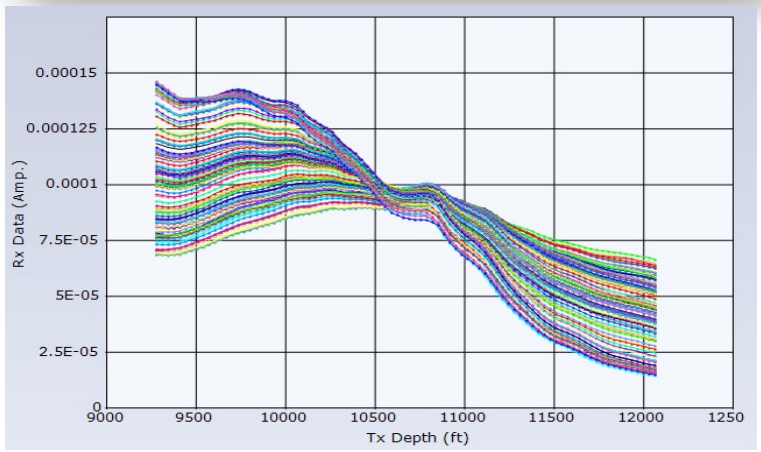
synthetic data



field-like data



Inverted model



coiled-tubing conveyance

140 data profiles acquired

6 days field operations

High data quality

inversions

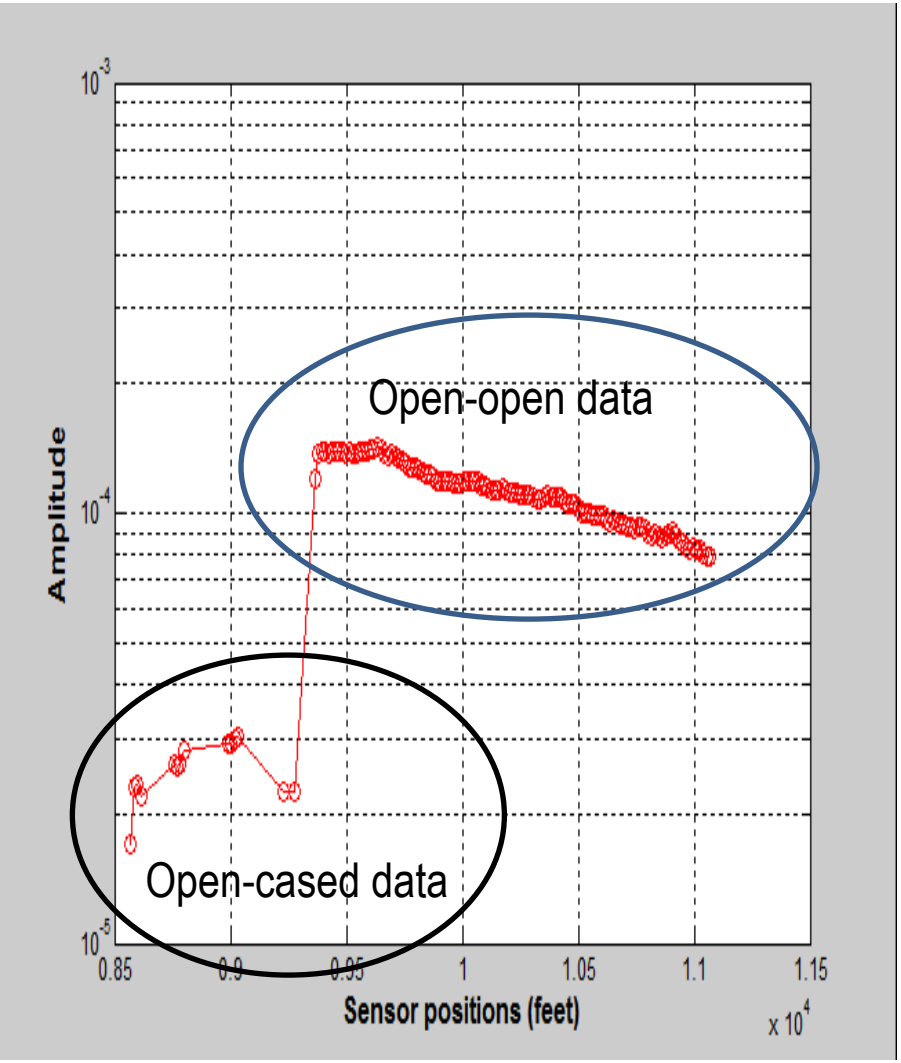
Resistivity structure

Inversion challenges

- How to integrate open-open and open-steel cased data
- How to handle 3D inversion with horizontal wells

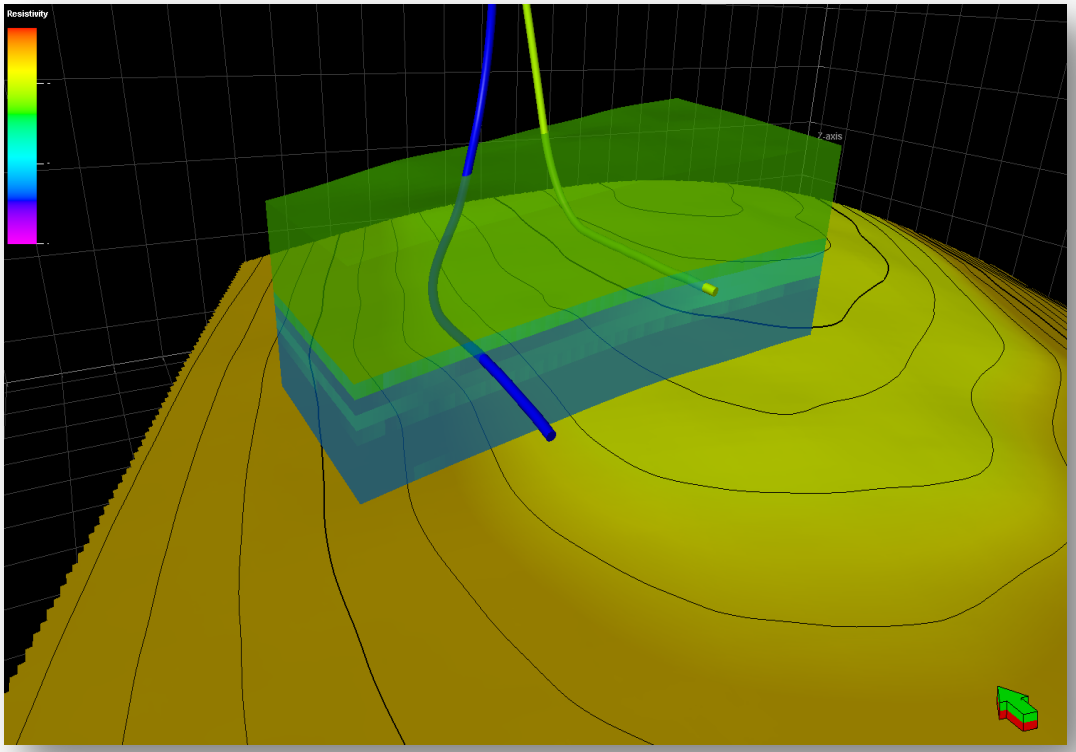
First challenge

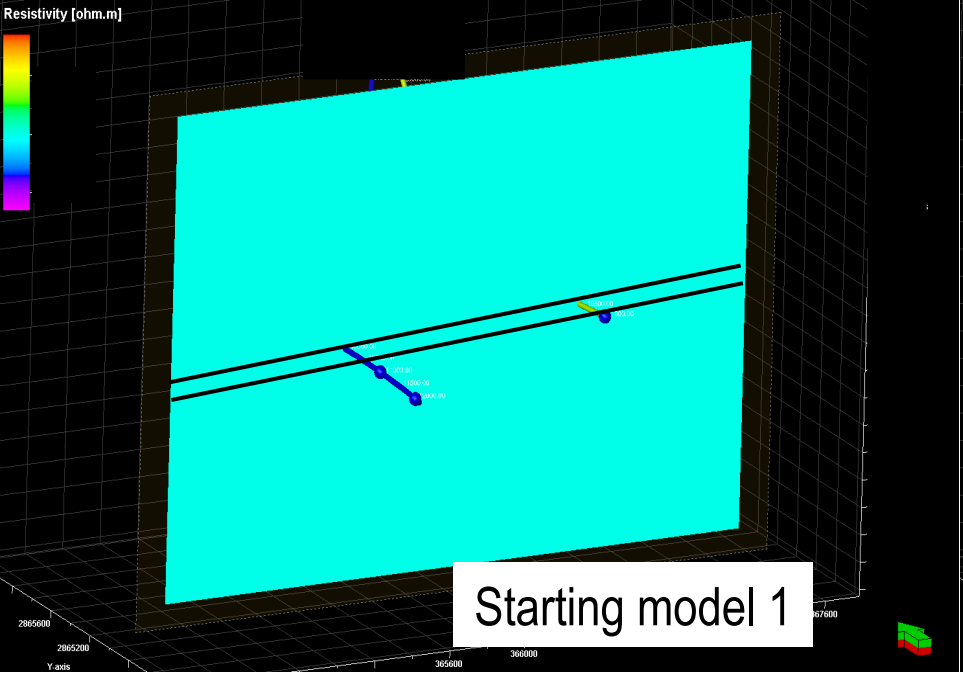
- Open-cased data is distorted
- Data correction has to be applied before inversion

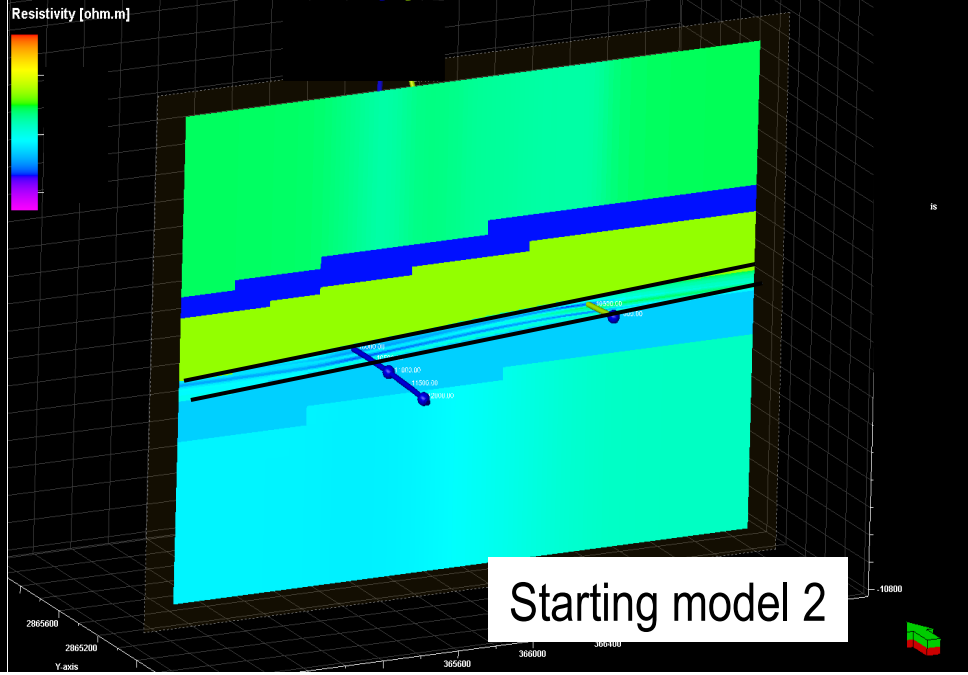


Second challenge

- Underdetermined problem:
  1. Model unknowns ~500,000
  2. Data points ~25,000
- Data are confined within thin reservoir
- Good starting model and constrains are needed to achieve useful inversion results




Resistivity [ohm.m]
Starting model 1
2865600
2865200
Y-axis
365600
366000
367600


Resistivity [ohm.m]
Starting model 2
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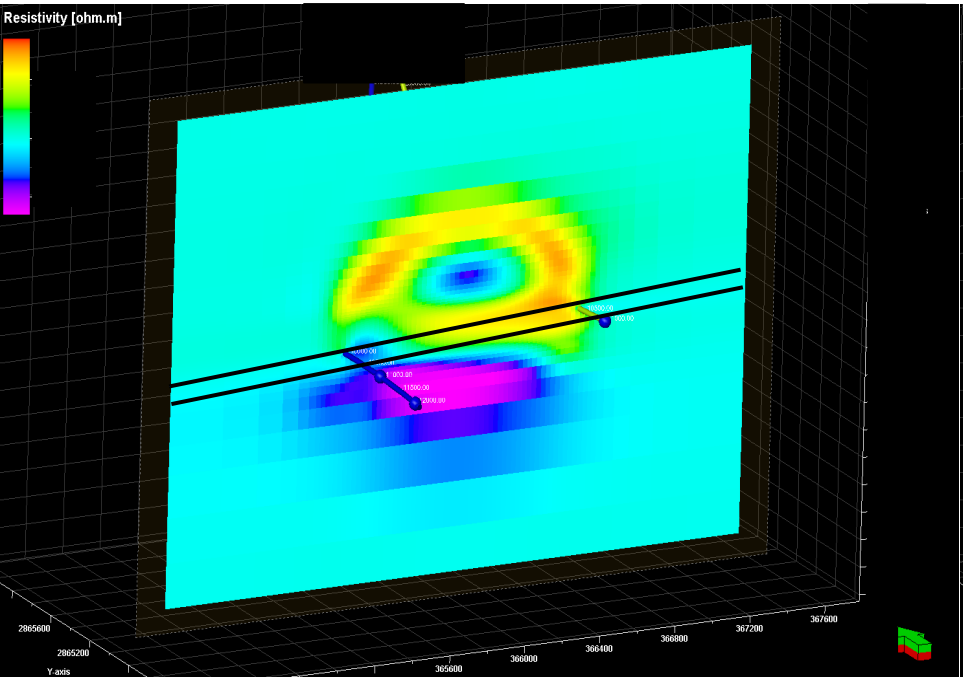
2865200
Y-axis
365600
366000
-10800


Resistivity [ohm.m]
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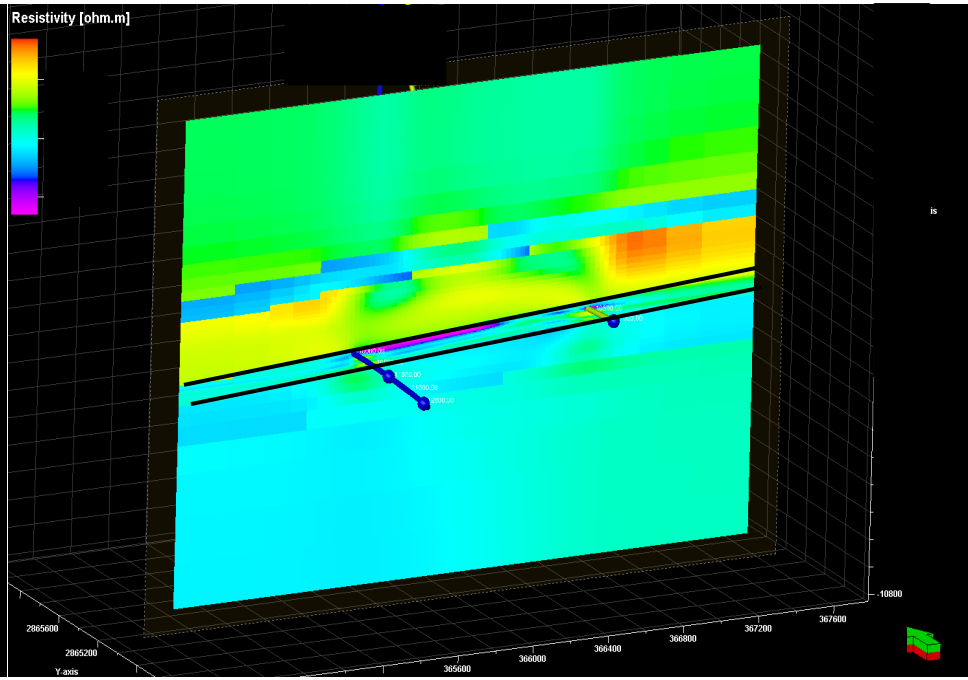
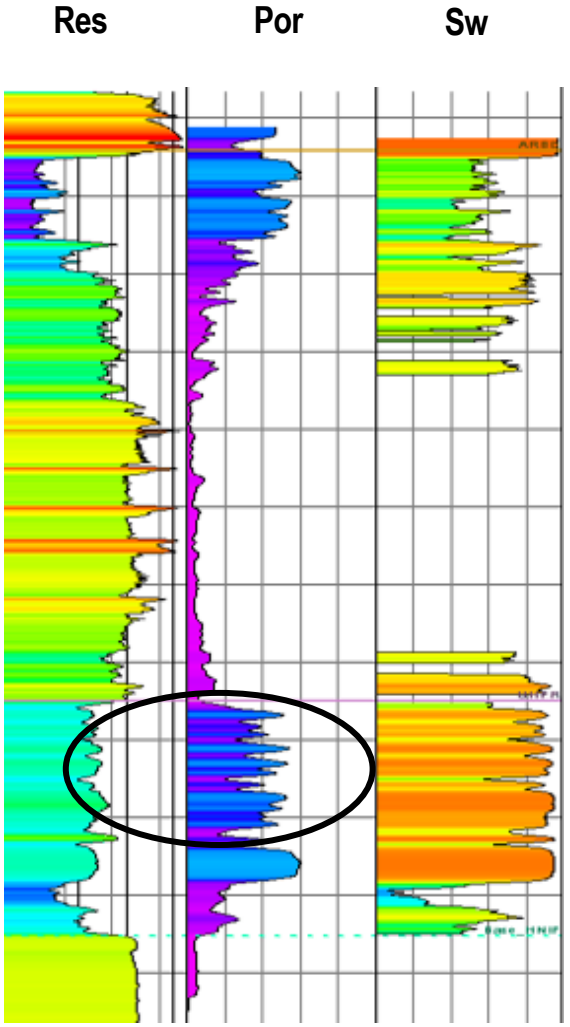
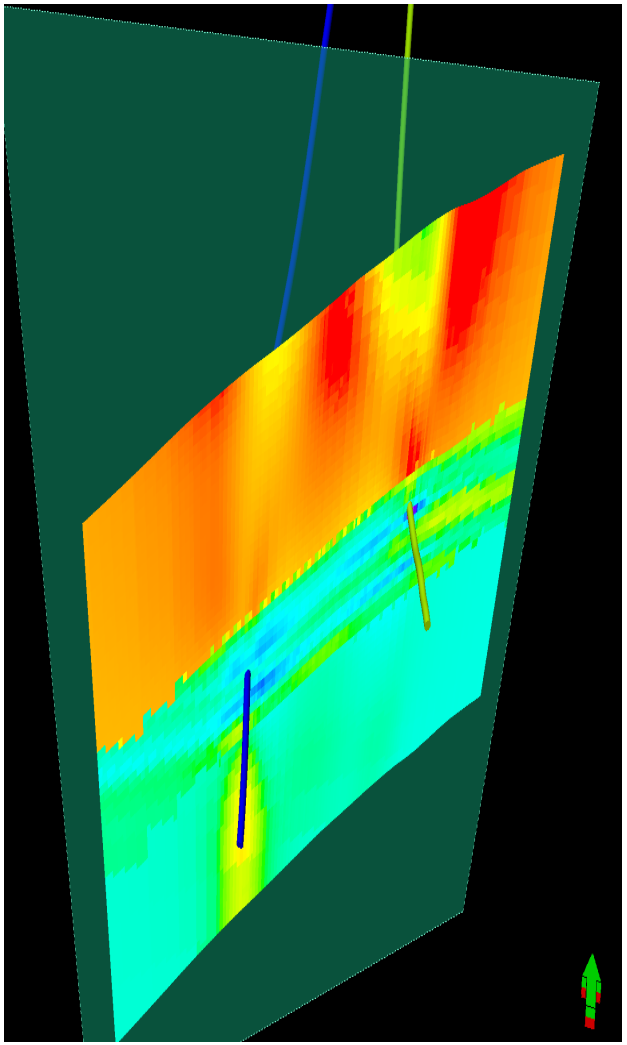
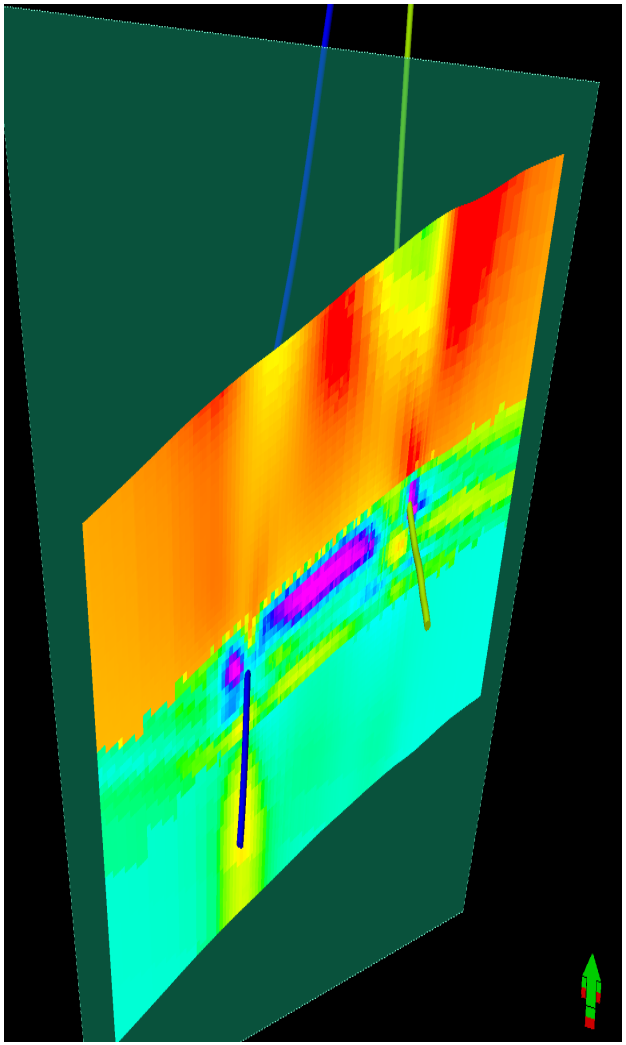
2865200
Y-axis
365600
366000
366400
366800
367200
367600

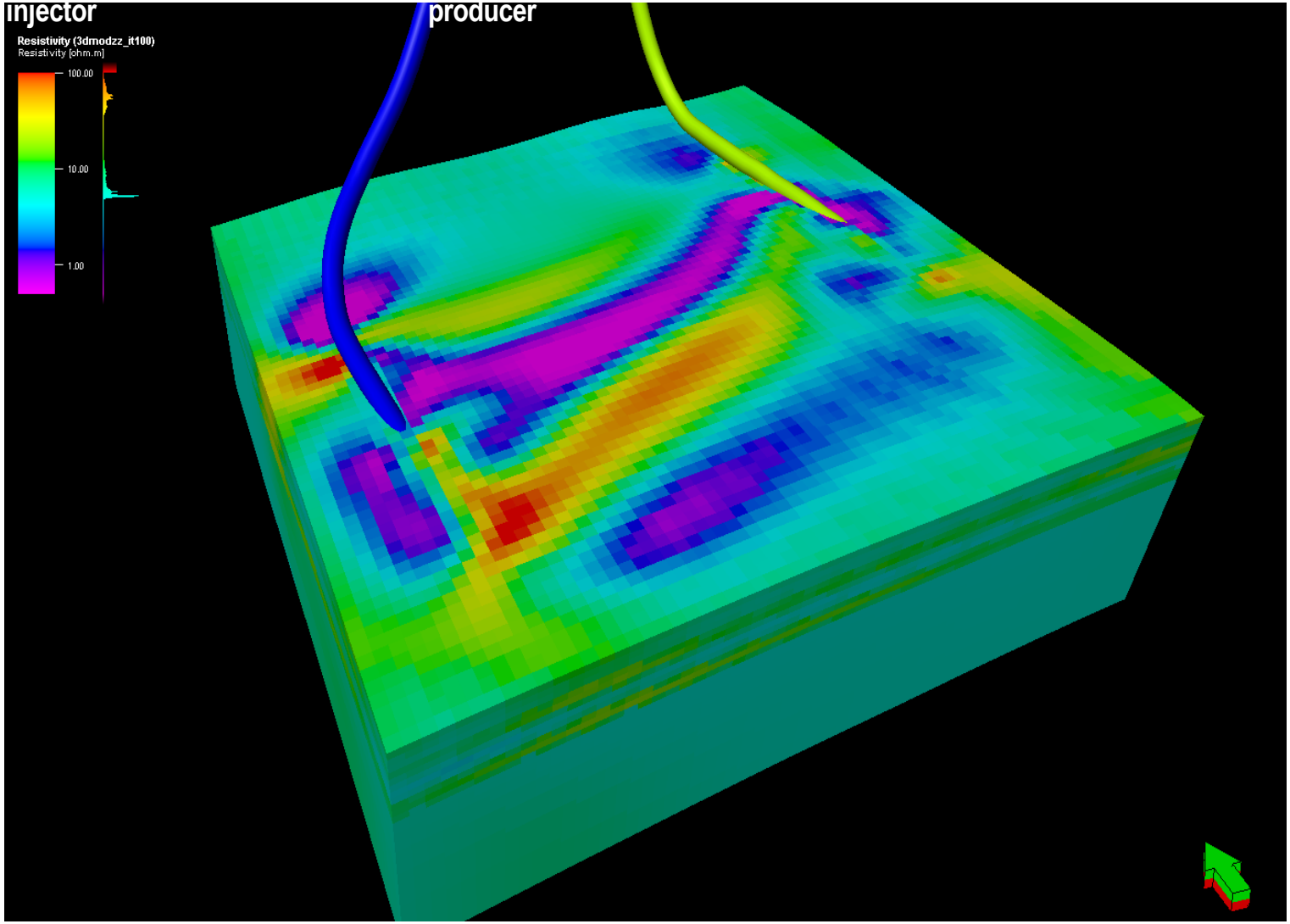

Resistivity [ohm.m]
2865600
2865200
Y-axis
365600
366000
366400
366800
367200
367600
-10800

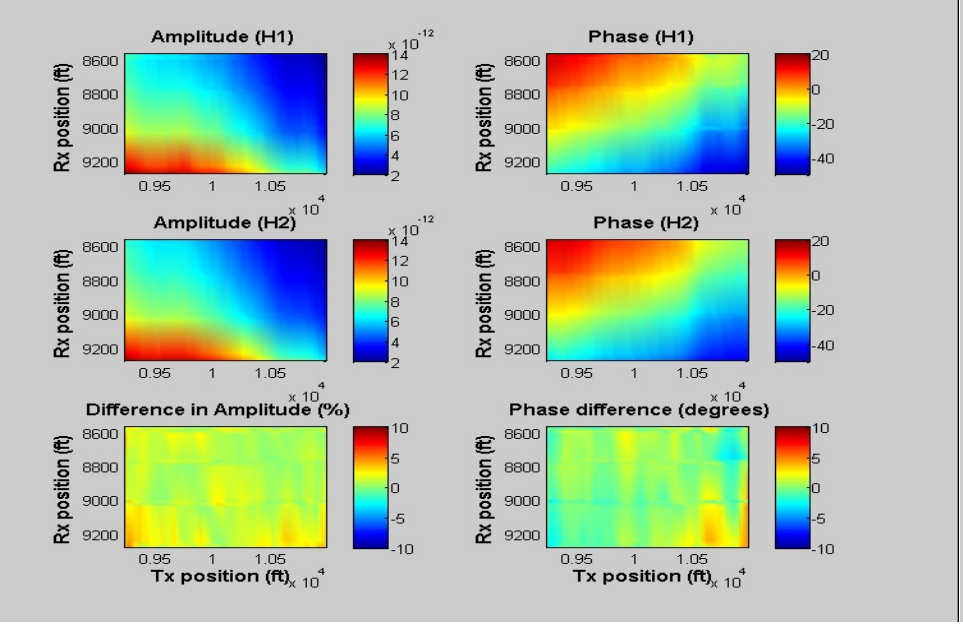
Interpretation Challenges: Inversion Non-Uniqueness



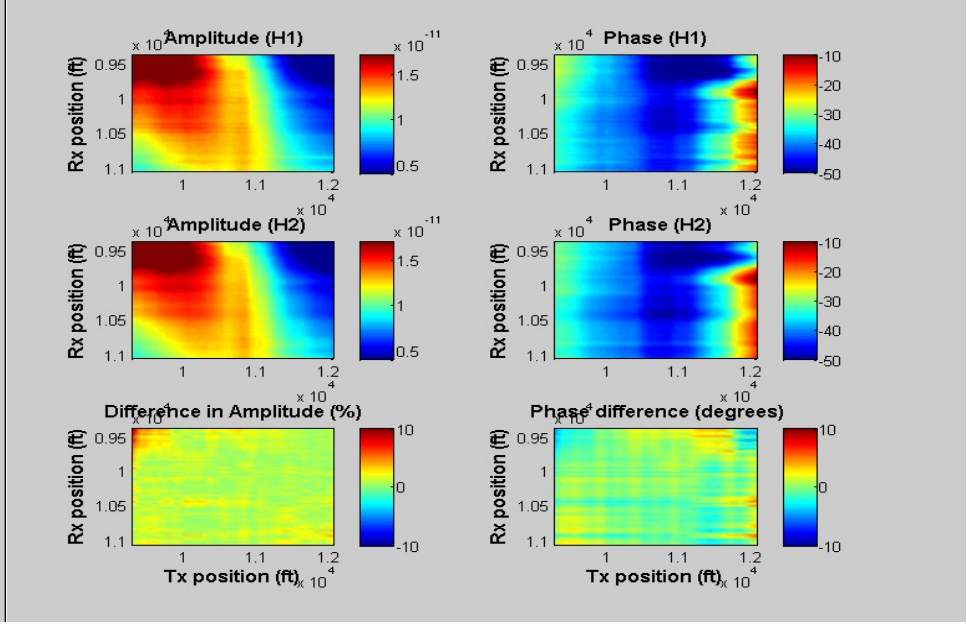




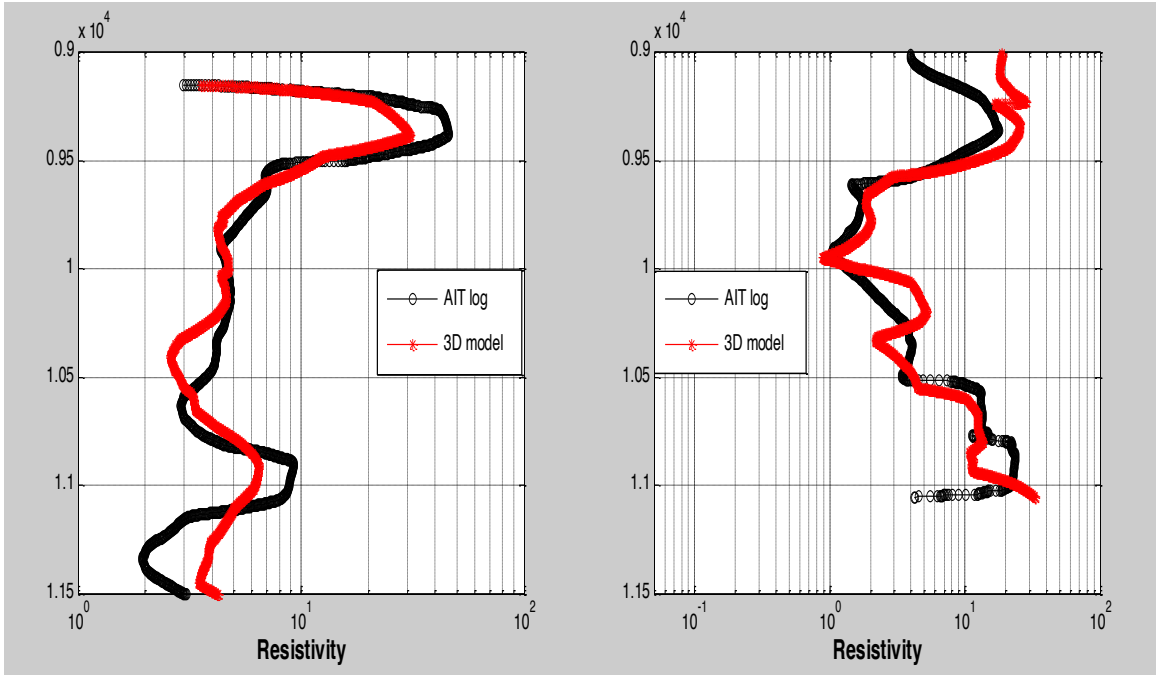

injector
producer
Resistivity (3dmodzz_it100)
Resistivity [ohm.m]
100.00
10.00
1.00



Data misfit for cased hole data



Data misfit for open hole data



Workflow (1)

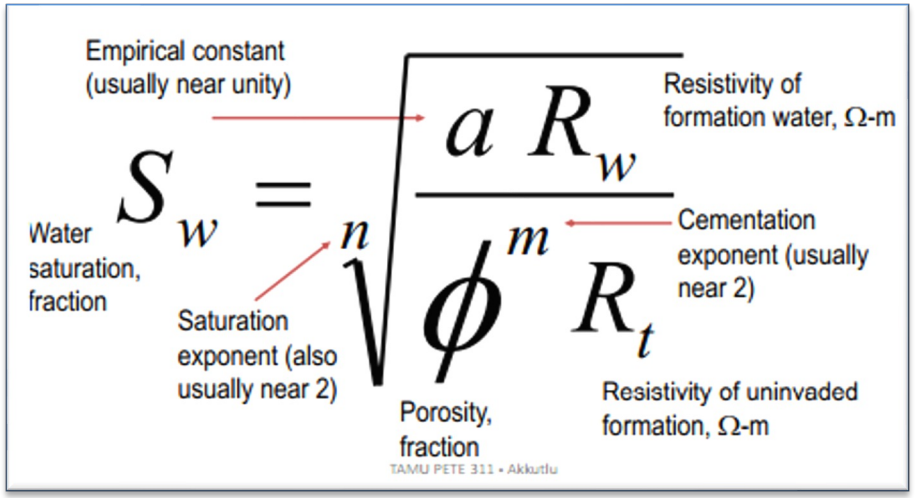
Φ

Rt

Rw

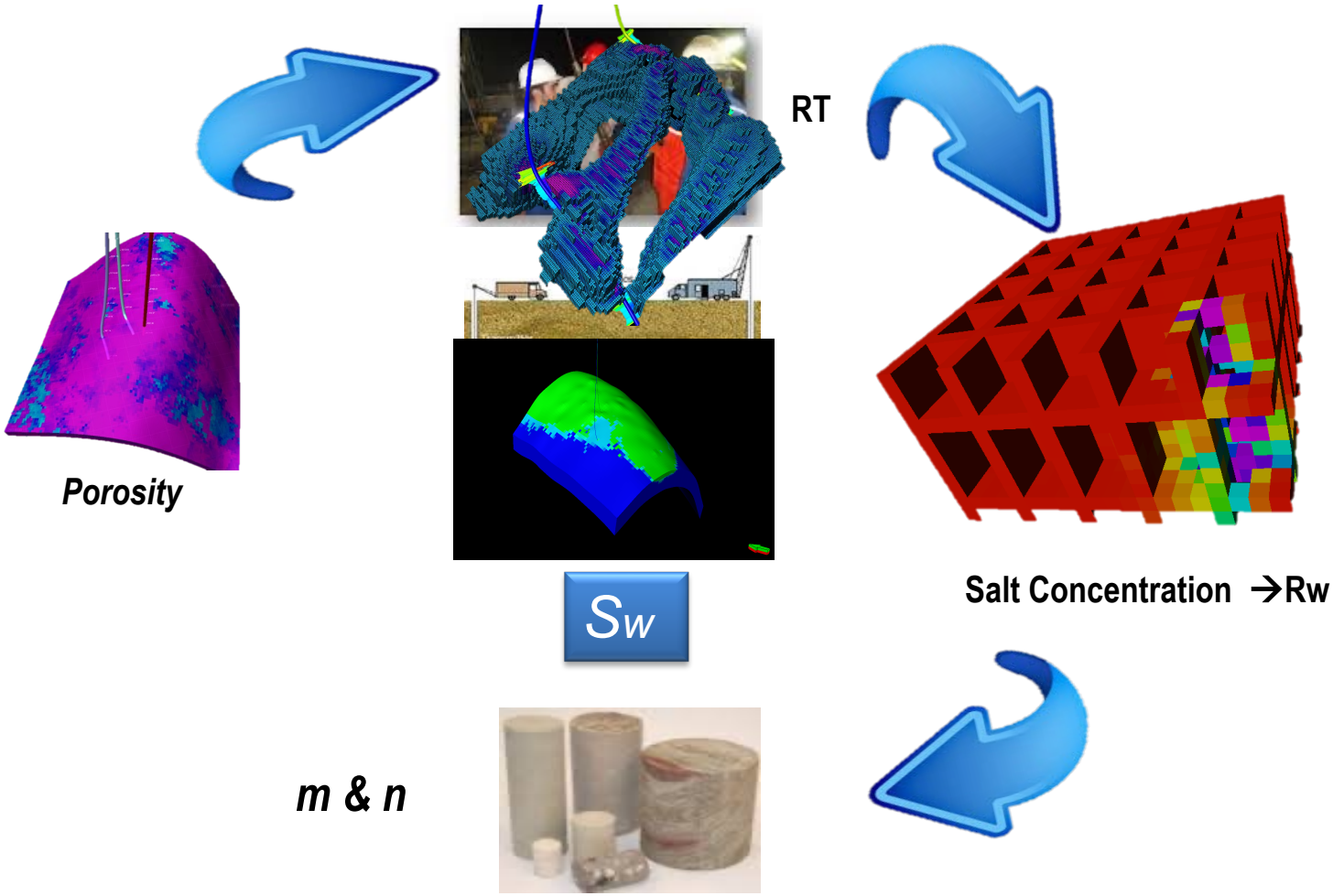
n

m

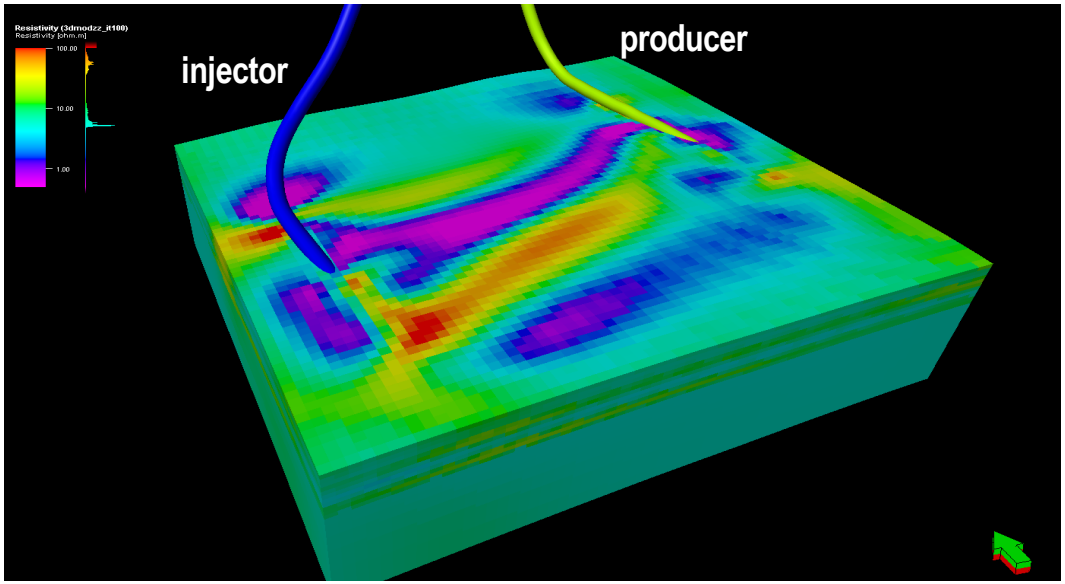


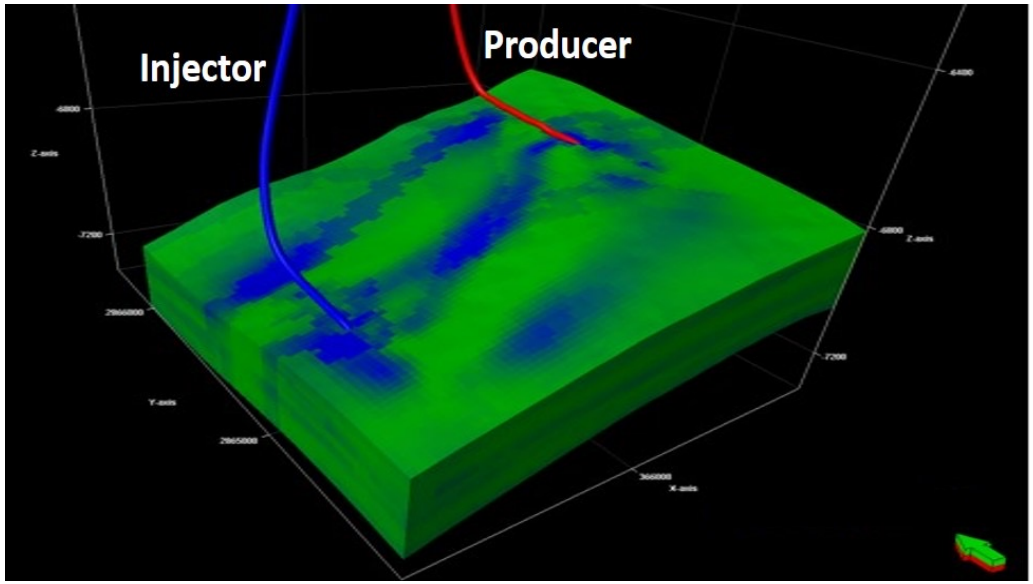
Sw

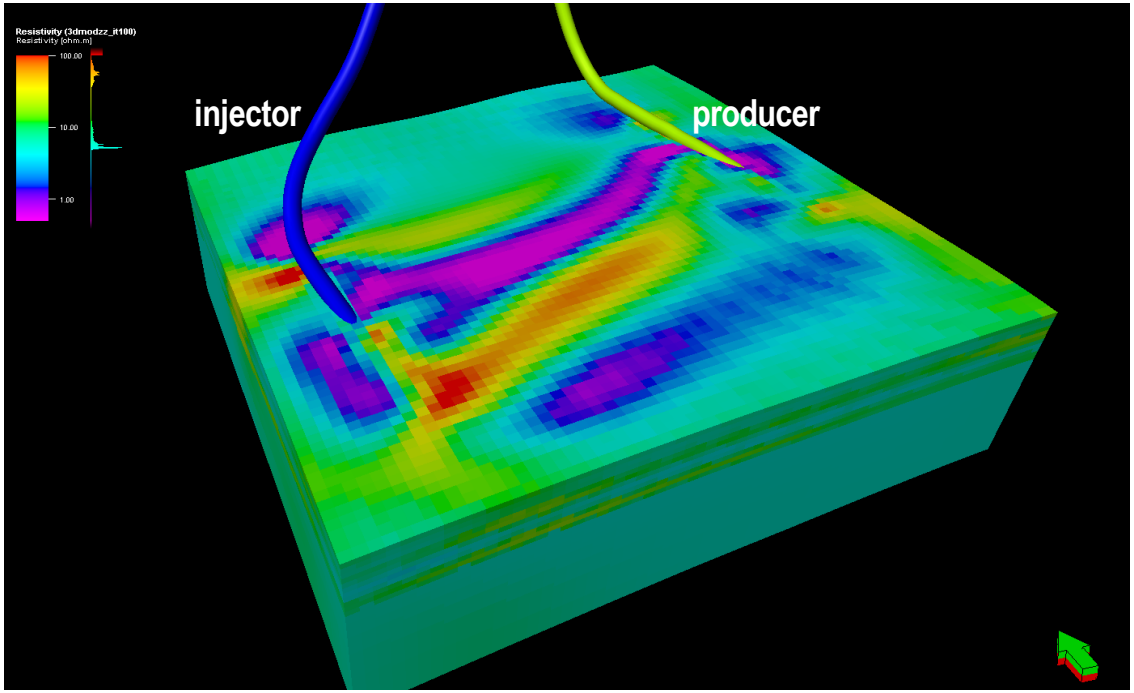
Workflow (2)

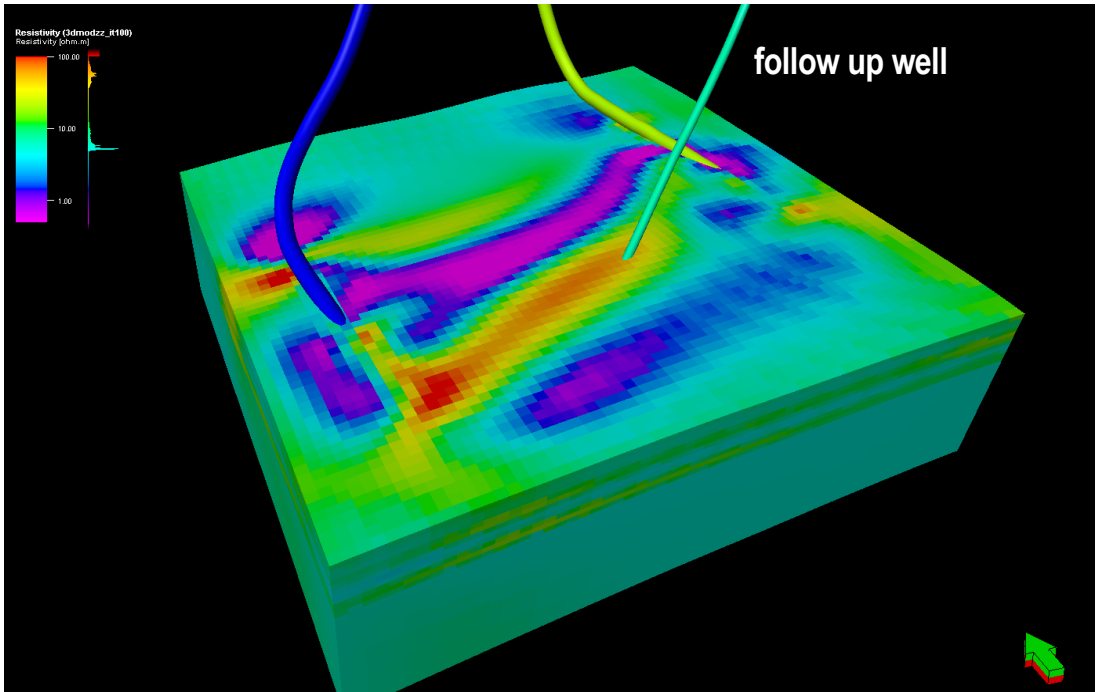


Saturation mapping






Resistivity (3dmodzz_it100)
Resistivity [ohm.m]
100.00
10.00
1.00
injector
producer


Resistivity (3dmodzz_it100)
Resistivity [ohm.m]
100.00
10.00
1.00
follow up well

Summary and conclusions

- Excellent resistivity imaging tool at reservoir scale
- Very efficient for monitoring fluid movements
- Capable to locate by-passed oil in a fractured reservoir
- Need two wells and providing 2D images
- Cannot work on two steel cased wells