# Leveraging 4D Seismic and Production Data to Advance the Geological Model of the Enfield Oil Field, Western Australia*

**Gillian Hamson[1]**

Search and Discovery Article #20172 (2012)**
Posted September 10, 2012

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012


[1]Woodside Energy Ltd., Perth, WA, Australia (gillian.hamson@woodside.com.au)

## Abstract

The Enfield Oil Field has been producing since 2006. The field was initially developed with 13 horizontal and deviated wells in a subsea development, with both updip and downdip water injection. Exceptional seismic resolution and time-lapse acquisition allowed valid conclusions to be drawn regarding changes in pressure and saturation across the field. An initial 4D Seismic monitor survey was acquired seven months after first oil; with a further two monitor surveys undertaken at two-year intervals. The dynamic information this provided, combined with production history, identified a number of infill and sidetrack opportunities. After three phases of infill drilling and five years of production, it became increasingly difficult to validate the existing static geological model against the latest well results and the dynamic behaviour of the field.

A thorough review of the conceptual geological model was undertaken, which included revising the depositional environment and stratigraphic correlation. The primary focus of the review was to integrate learnings from 4D Seismic and individual well production histories. Some injector-producer well pairs were performing as expected while others appeared to be affected by barriers and baffles that were beyond 3D seismic resolution. The dynamic information was used to ensure that the stratigraphic correlation was both geologically valid and matched to actual field behaviour. Well results and detailed core characterisation led to a change in interpreted depositional environment, with one zone originally identified as shoreface deposits re-defined as the product of a deep-marine depositional system. Pressure and saturation signals from 4D seismic, as well as pressure data and fluid type information from infill wells permitted an improved understanding of fault seal and compartmentalisation. Better than expected recovery in some parts of the field led to an inferred field-wide flooding surface being re-interpreted as a series of shingled, non-continuous shales, acting as baffles rather than a barrier to vertical flow. Fundamental changes in depositional and architectural concepts arising from the integration of static and dynamic datasets necessitated a comprehensive re-build of the static reservoir model. The new static model was used to

match field production history more accurately, thereby providing greater confidence about the distribution of remaining reserves and potential infill drilling targets.

# Leveraging 4D seismic and production data to advance the geological model of the Enfield Oil Field, Western Australia.

**Gillian Hamson**

Senior Development Geologist

AAPG Annual Convention & Exhibition, Long Beach, California

25 April 2012

woodside

# Disclaimer and important notice

This presentation contains forward looking statements that are subject to risk factors associated with oil and gas businesses. It is believed that the expectations reflected in these statements are reasonable but they may be affected by a variety of variables and changes in underlying assumptions which could cause actual results or trends to differ materially, including but not limited to: price fluctuations, actual demand, currency fluctuations, drilling and production results, reserve estimates, loss of market, industry competition, environmental risks, physical risks, legislative, fiscal and regulatory developments, economic and financial market conditions in various countries and regions, political risks, project delay or advancement, approvals and cost estimates.

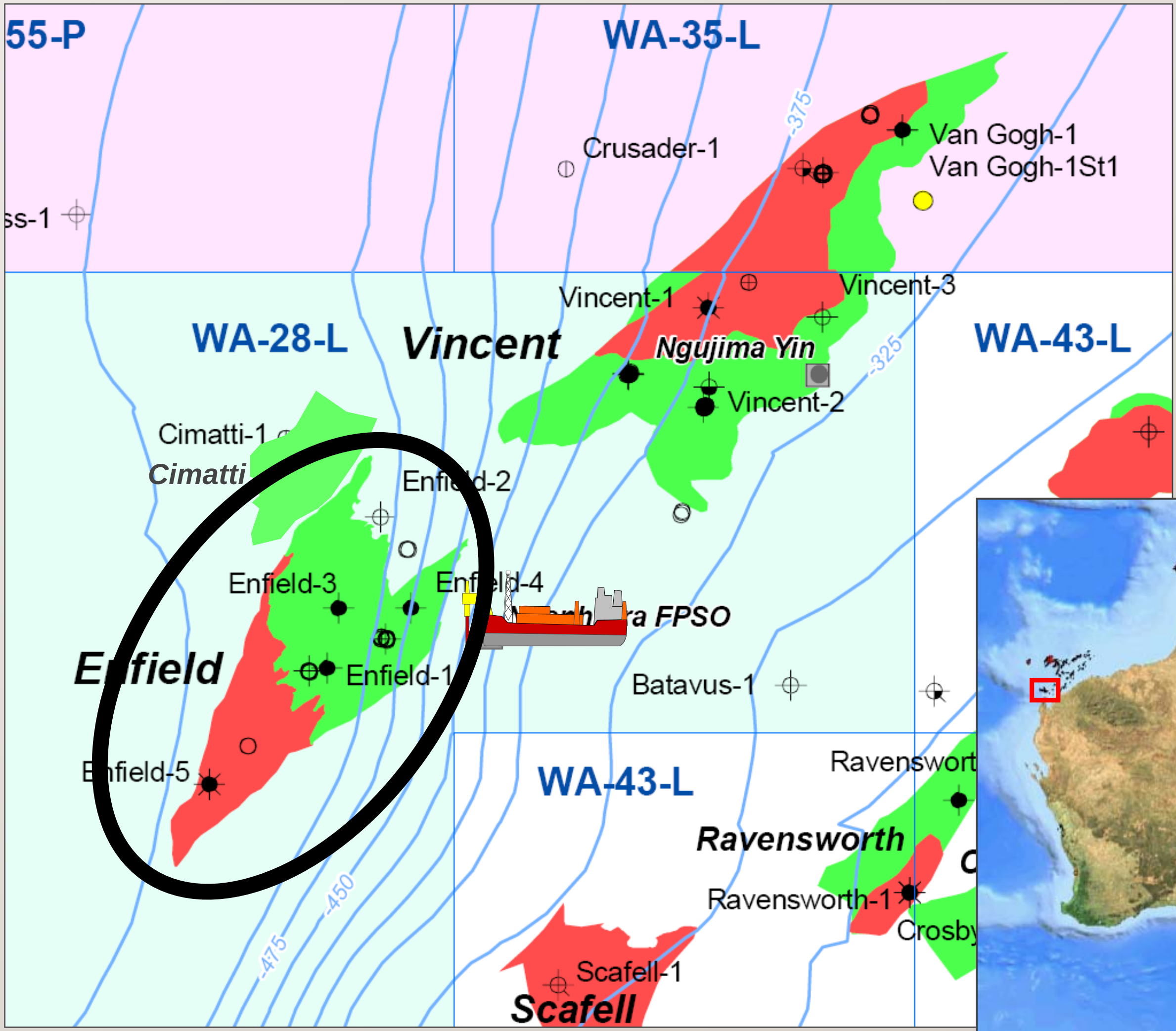
All references to dollars, cents or $ in this presentation are to Australian currency, unless otherwise stated.

References to “Woodside” may be references to Woodside Petroleum Ltd. or its applicable subsidiaries.

# Aim: Increase in data & knowledge through time

1. Enfield Introduction
2. Exploration/Appraisal Wells (1999-2003)
3. Field Development Plan (2004)
4. Development Drilling (2004-2006)
5. Initial Production Data (mid 2006)
6. 4D Seismic Monitor Surveys (Sept 2007- Dec 2008)
7. Infill Drilling (Mid 2009 & 2010)
8. Conclusions

# Enfield Location



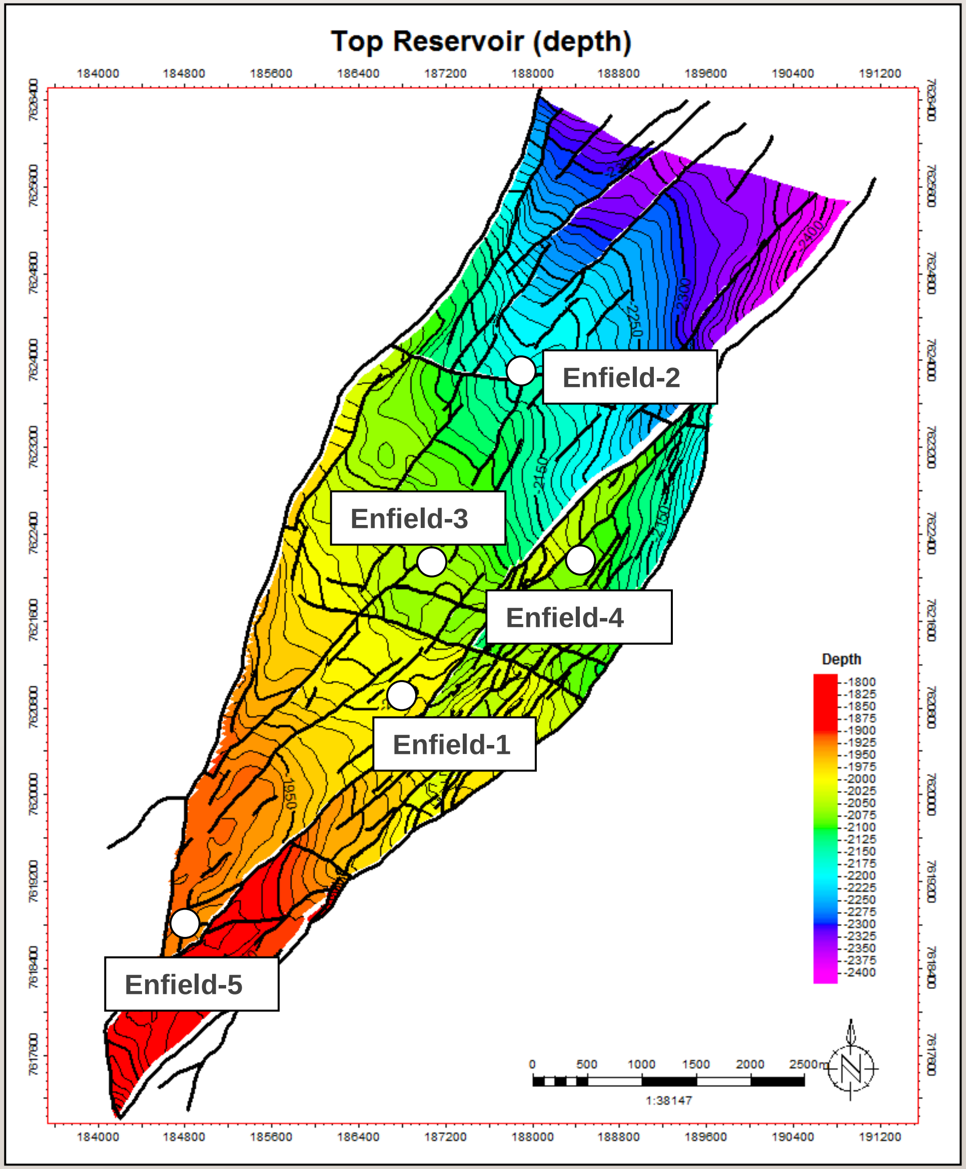

# Enfield Field Introduction

| Basic information | |
|---|---|
| Field Discovered | March 1999 |
| First Production | July 2006 |
| Licence | WA-28-L |
| Basin | Exmouth Sub-basin, WA |
| JV | Woodside (60%)<br>Mitsui (40%) |
| Water Depth | 500-550 m |
| Datum | 2060 mss<br>3057 psia (initial)<br>74°C |

| Reservoir & fluid properties | |
|---|---|
| Reservoir | Macedon Fmn (Late Jurassic) |
| Reservoir Properties | ~24% porosity<br>~500-2000 mD<br>~80% NTG |
| Oil Properties | 22°API<br>GOR = 320 scf/stb<br>2.2 cp viscosity<br>FVF = 1.14 $m^3/m^3$ |

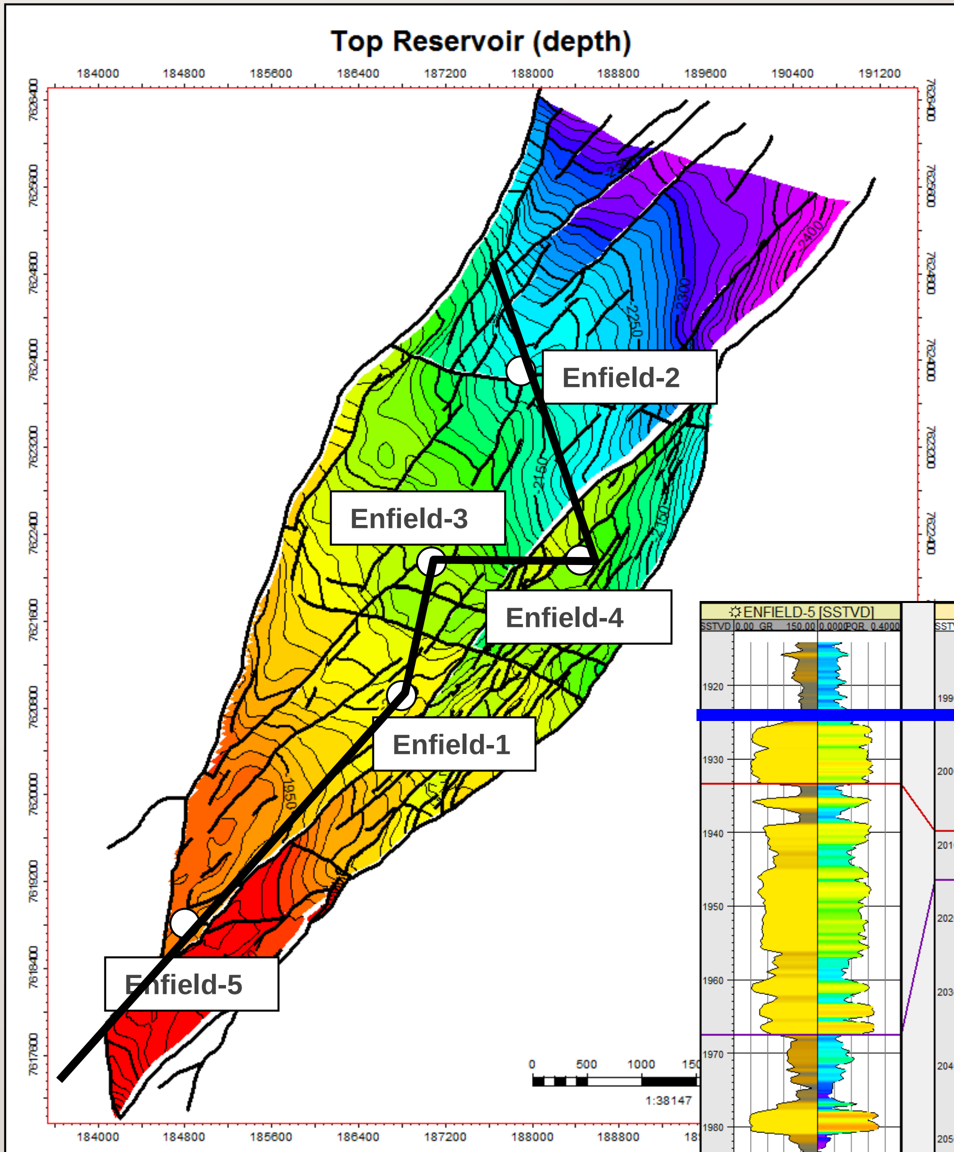
| Key Field Metrics | | |
|---|---|---|
| **Initially In Place** | **MMstb** | **~225** |
| **Ultimate Recovery** | **MMstb** | **~90** |
| **Recovery Factor** | **%** | **~40** |

# Exploration and Appraisal Wells




- **Enfield-1** spudded in March 1999
  - 22 m oil column (ODT)
  - Excellent quality reservoir, 1-2 reservoir zones
  - MDT pressure data indicates one column
- **Enfield-2** spudded in June 1999
  - 25 m fully water-bearing reservoir interval
  - Poorer quality reservoir, 1-2 reservoir zones
  - Core indicates heterolithic, bioturbated reservoir
- **Enfield-3** spudded in September 2000
  - 52 m oil column (ODT)
  - Excellent reservoir quality, 2 reservoir zones
  - Core indicates structureless 100% NTG reservoir
- **Enfield-4** spudded in January 2002
  - 18 m oil column (ODT)
  - Excellent reservoir quality, 1 reservoir zone
  - Proves good res quality in dimmer seismic area
- **Enfield-5** spudded in September 2002
  - 43 m gas column with 2 oil columns (perched?)
  - Excellent reservoir quality, 2 reservoir zones
  - Potential GOC intersected
  - Oil gradient differs from previous wells

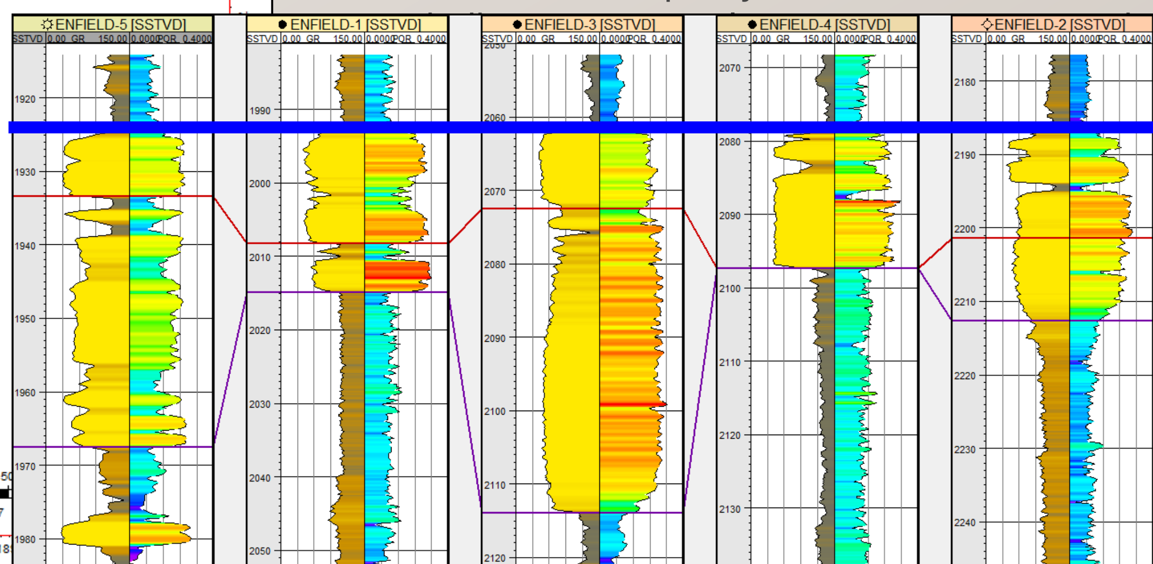
# Exploration and Appraisal Wells



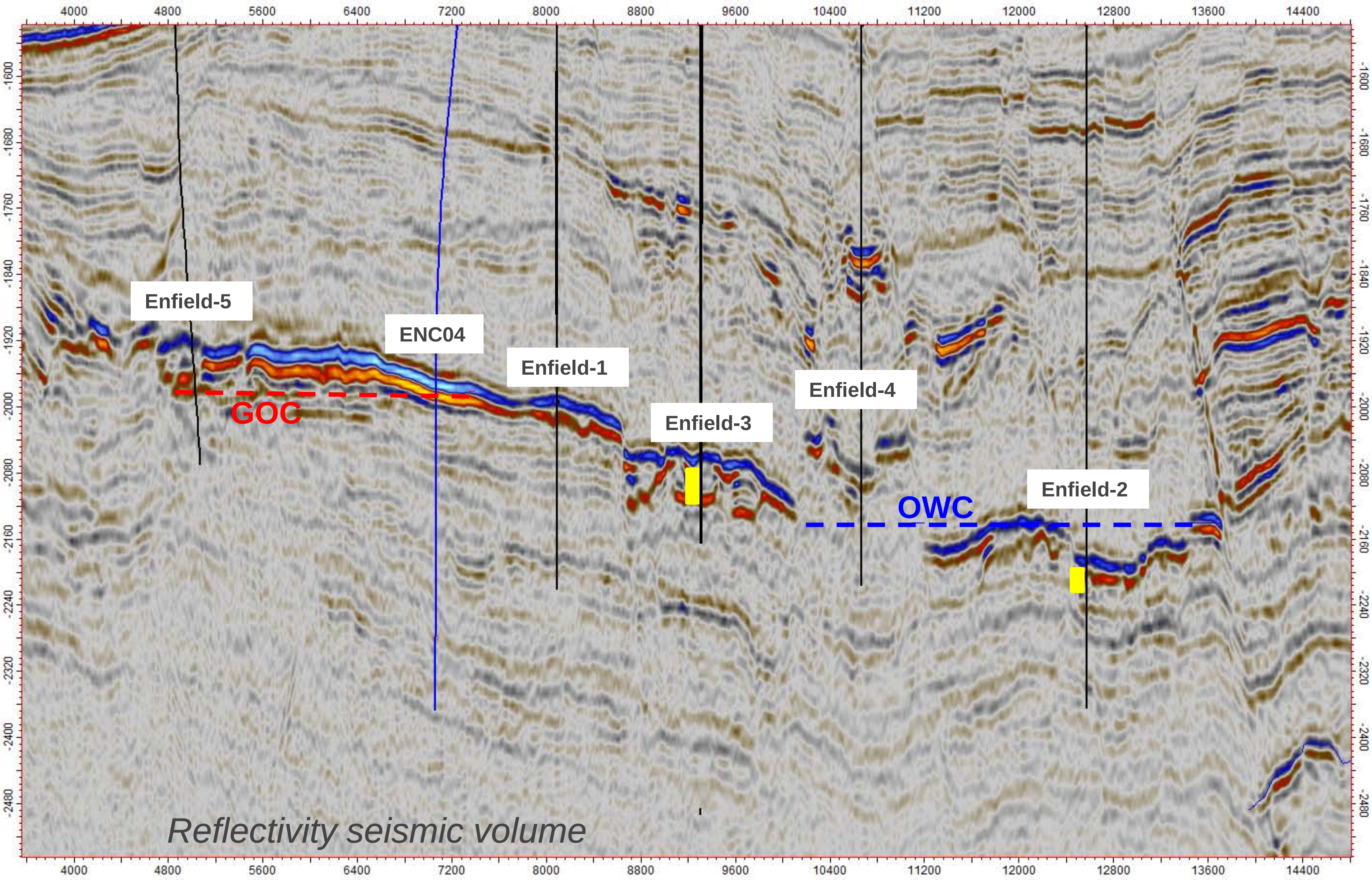

- **Enfield-1** spudded in March 1999
- 22 m oil column (ODT)
- Excellent quality reservoir, 1-2 reservoir zones
- MDT pressure data indicates one column

- **Enfield-2** spudded in June 1999
- 25 m fully water-bearing reservoir interval
- Poorer quality reservoir, 1-2 reservoir zones
- Core indicates heterolithic, bioturbated reservoir

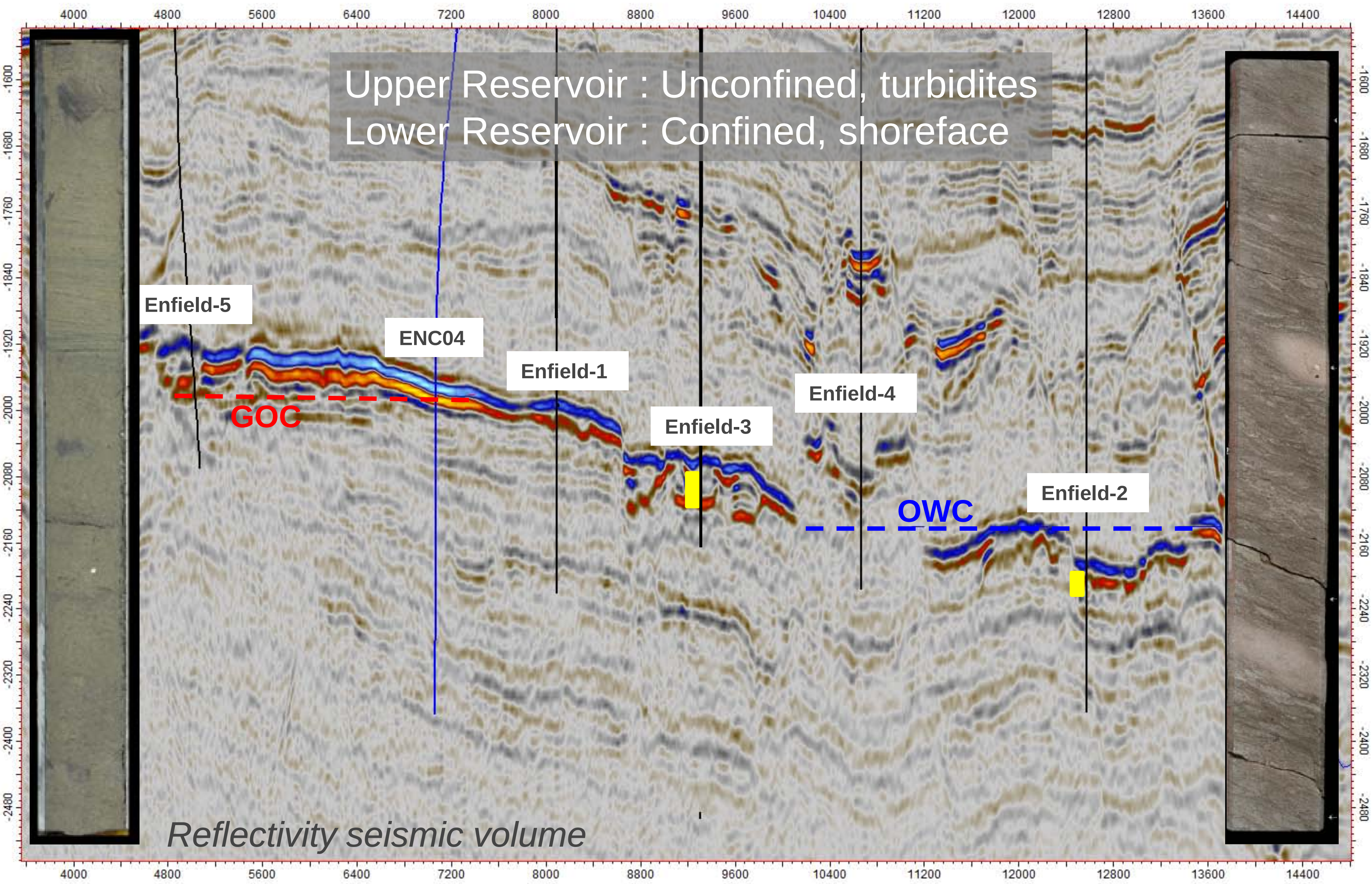
- **Enfield-3** spudded in September 2000
- 52 m oil column (ODT)
- Excellent reservoir quality, 2 reservoir zones



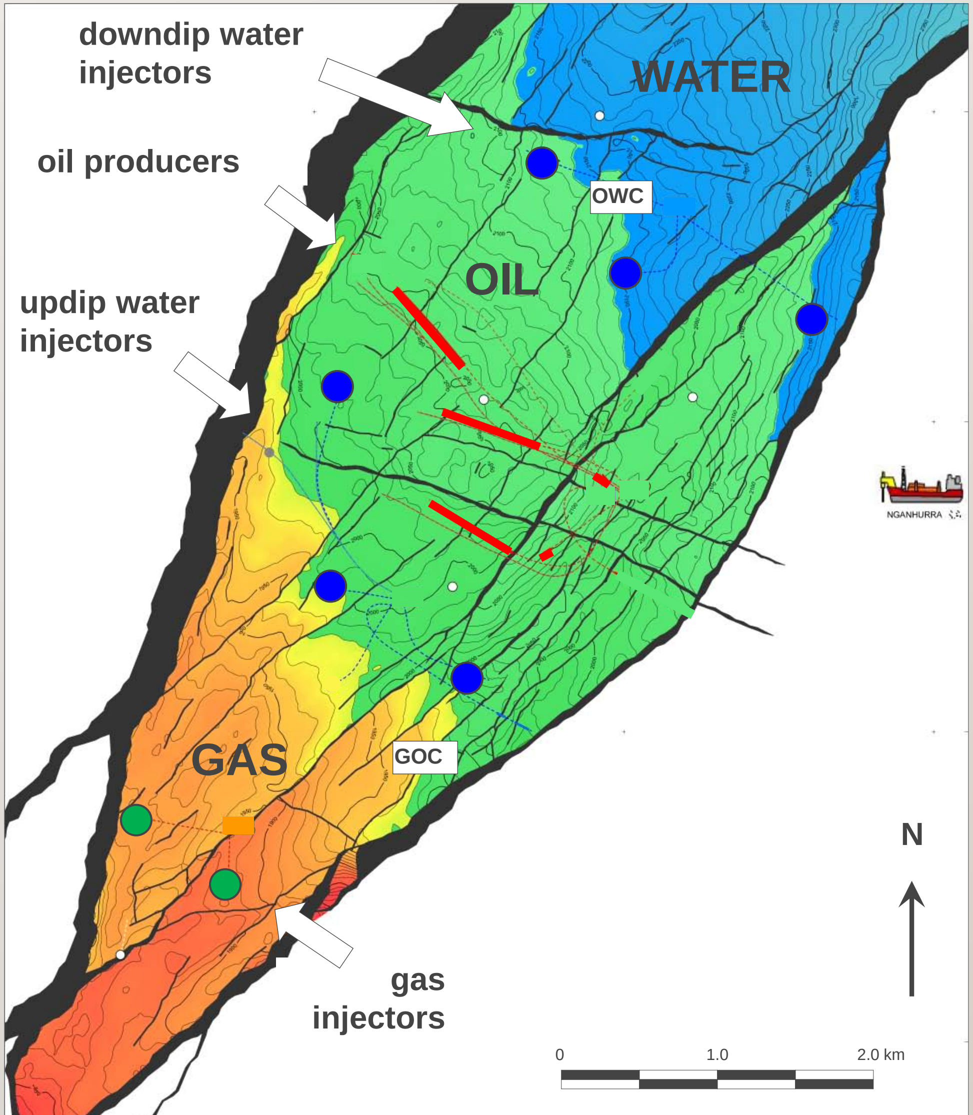
# Initial geological understanding:
# 5 appraisal wells; 50m core from two wells

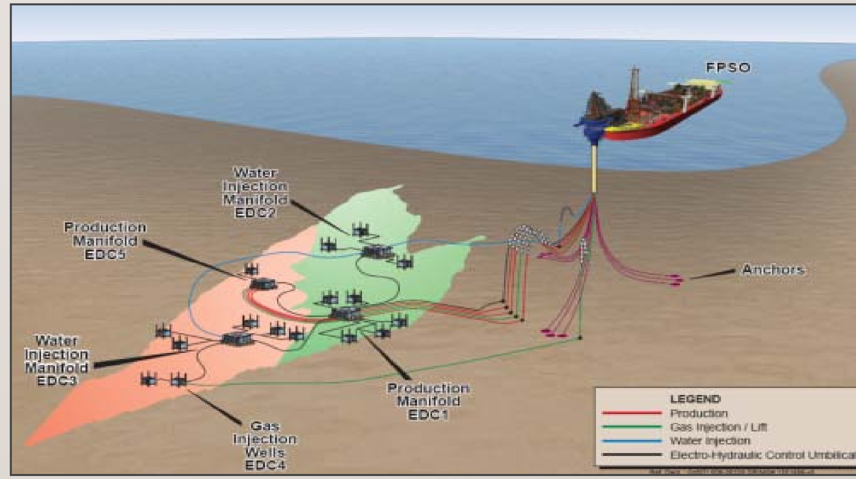


# Initial geological understanding:
# 5 appraisal wells; 50m core from two wells



# Field Development Plan




## Nganhurra FPSO

**Oil capacity:** 100,000 bopd

**Produced water:** 125,000 bwpdx

**Water injection:** 140,000 bwpd

**Gas:** 80 MMscf/d

**Crude storage:** 900,000 bbl

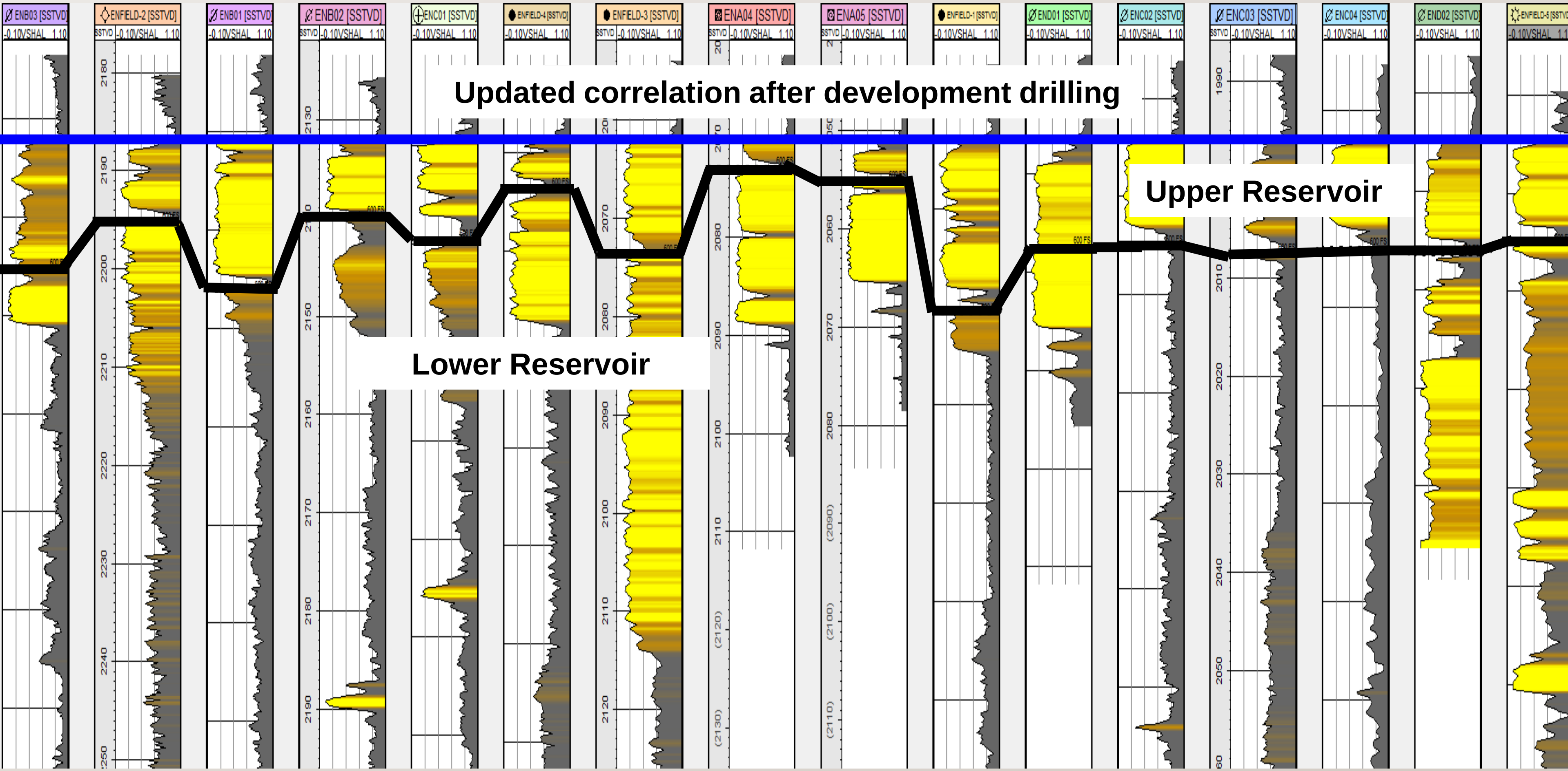
## Key Uncertainties

- STOIIP
- Sweep efficiency (unswept areas)
- Water-breakthrough in Horst and Sliver
- Residual oil
- Reservoir Souring

# Aim: Increase in data & knowledge through time

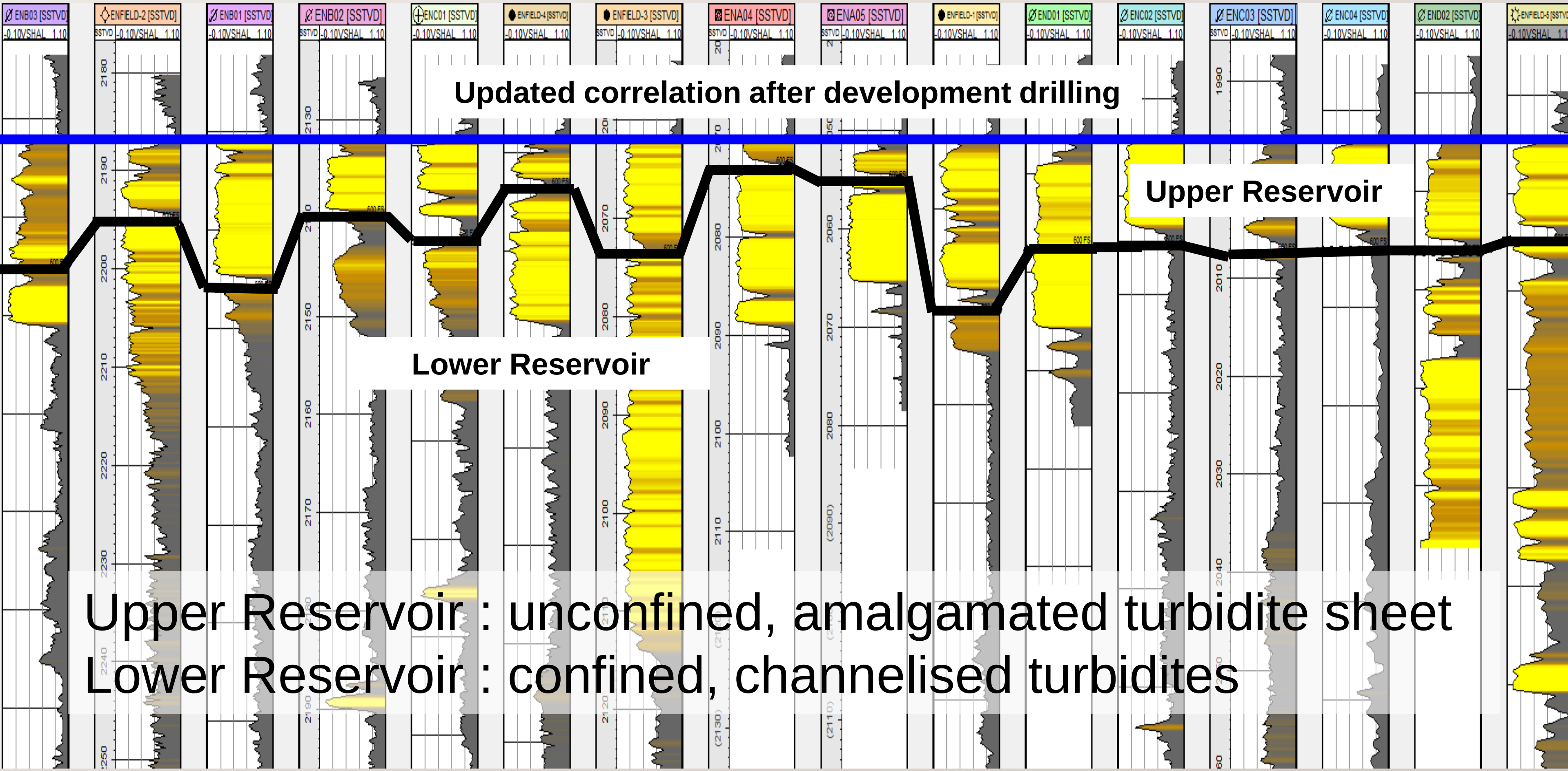
1. Enfield Introduction
2. Exploration/Appraisal Wells (1999-2003)
3. Field Development Plan (2004)
4. Development Drilling (2004-2006)
5. Initial Production Data (mid 2006)
6. 4D Seismic Monitor Surveys (Sept 2007- Dec 2008)
7. Infill Drilling (Mid 2009 & 2010)
8. Conclusions

# Development drilling:
# 13 wells; ~2670m reservoir penetration




- Environment of deposition re-interpreted as deep marine for both reservoirs
- Flooding surface separating Upper from Lower Reservoir picked in all wells
- Behaves as a barrier to vertical flow in dynamic model

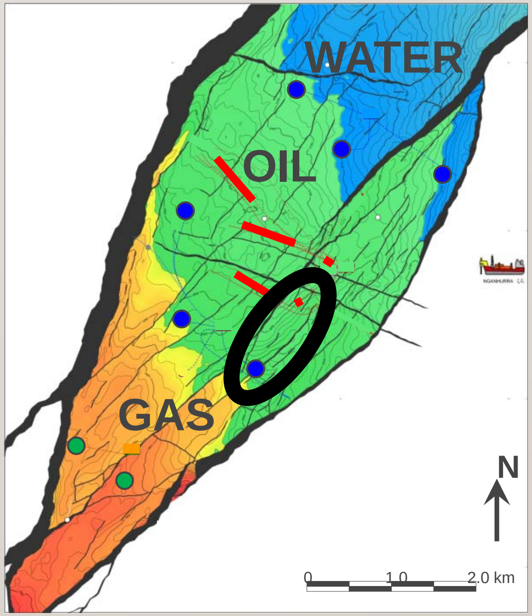
# Development drilling:
# 13 wells; ~2670m reservoir penetration

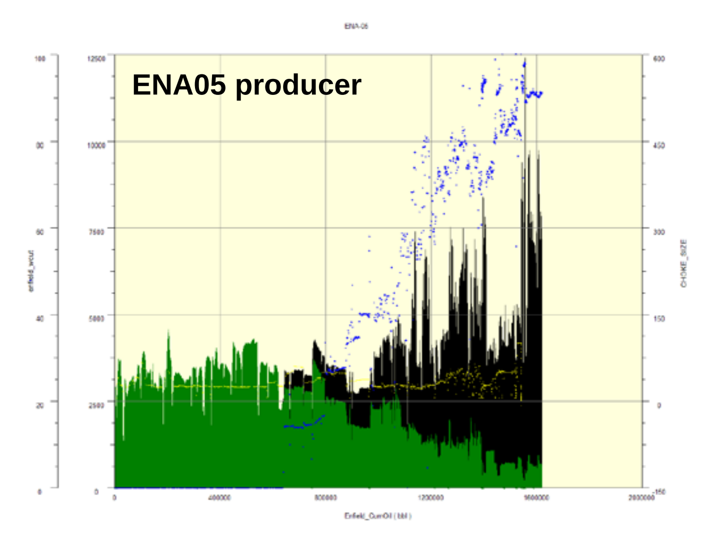



- Environment of deposition re-interpreted as deep marine for both reservoirs
- Flooding surface separating Upper from Lower Reservoir picked in all wells
- Behaves as a barrier to vertical flow in dynamic model

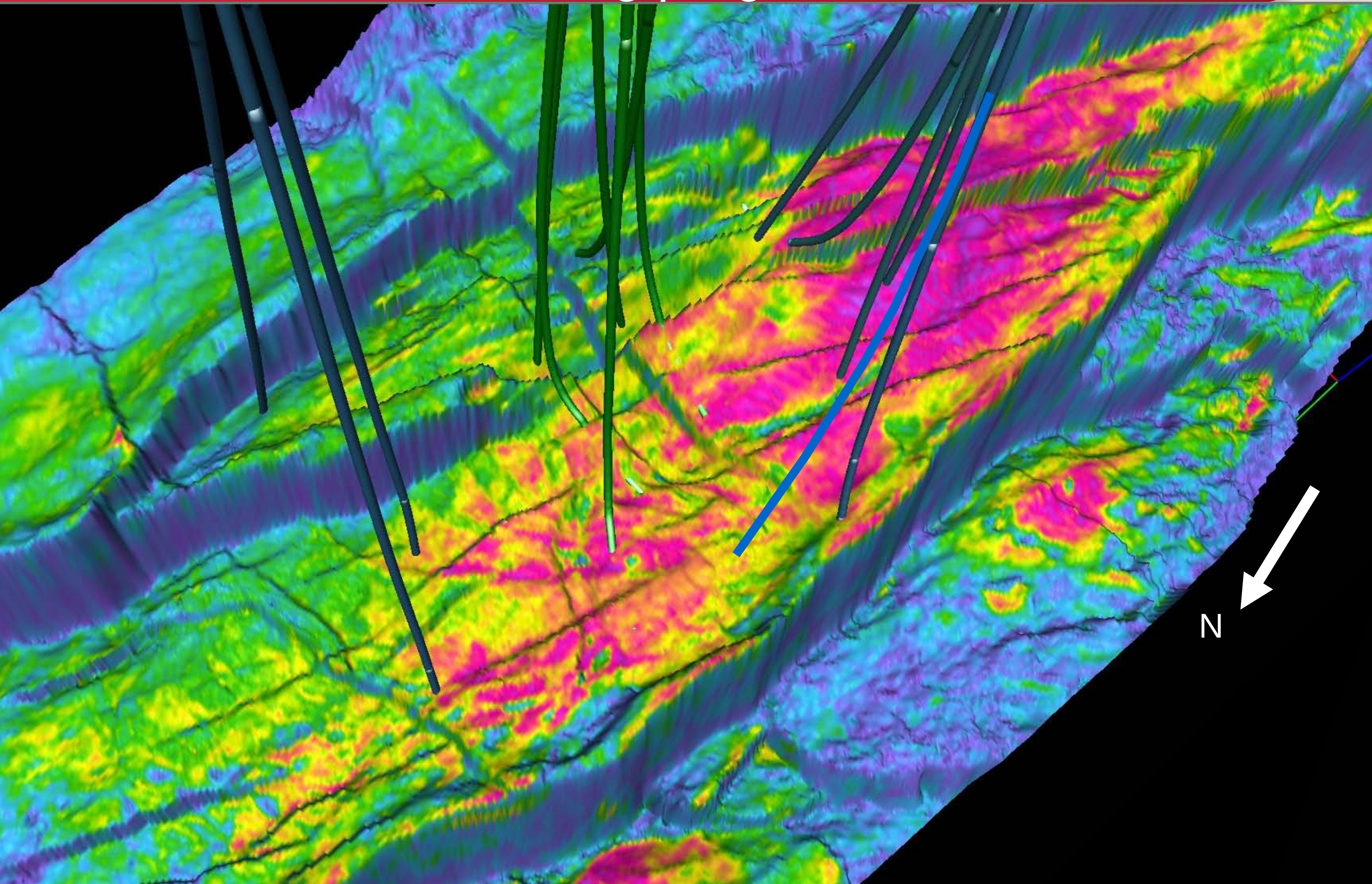
# Early production insights: well data

- Fault behaviour not in line with pre-development fault transmissibility model
- Sand-sand juxtaposition at faults not necessary for connectivity in some areas
- North-south trending faults appear to act as barriers, while major east-west faults appear to have produced key flow paths
- Early water breakthrough in ENA05 & ENA03 production wells
- Large scale vertical and areal reservoir connectivity appears likely



# Early production insights:
# 4D seismic monitoring program



# Early production insights:
# 4D seismic monitoring program

Complexity of….

- Reservoir stratigraphy & structure,
- Fluid movements with water injection,
- & Mobile gas cap

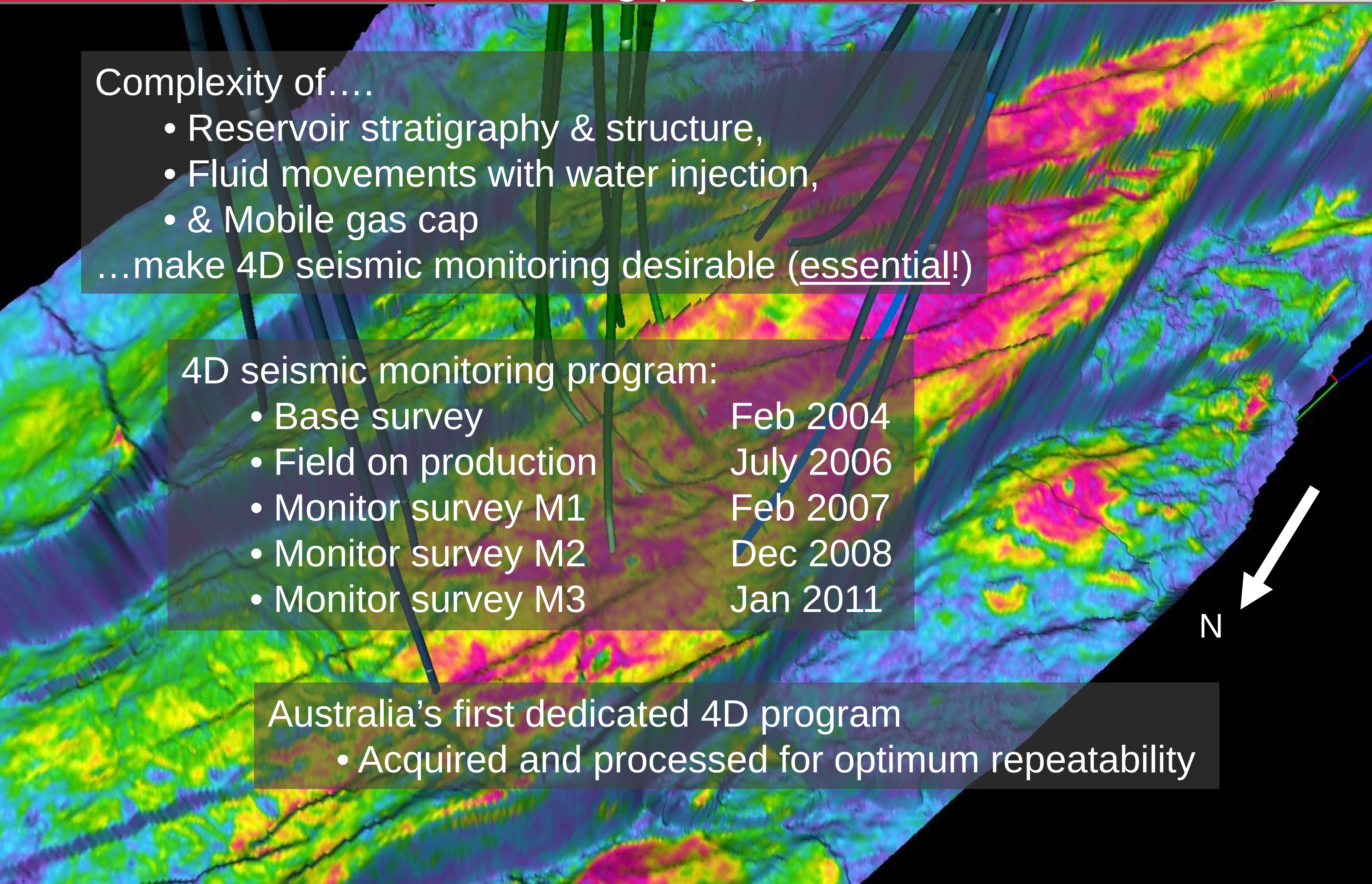
…make 4D seismic monitoring desirable (<u>essential</u>!)

4D seismic monitoring program:

| | |
|---|---|
| • Base survey | Feb 2004 |
| • Field on production | July 2006 |
| • Monitor survey M1 | Feb 2007 |
| • Monitor survey M2 | Dec 2008 |
| • Monitor survey M3 | Jan 2011 |

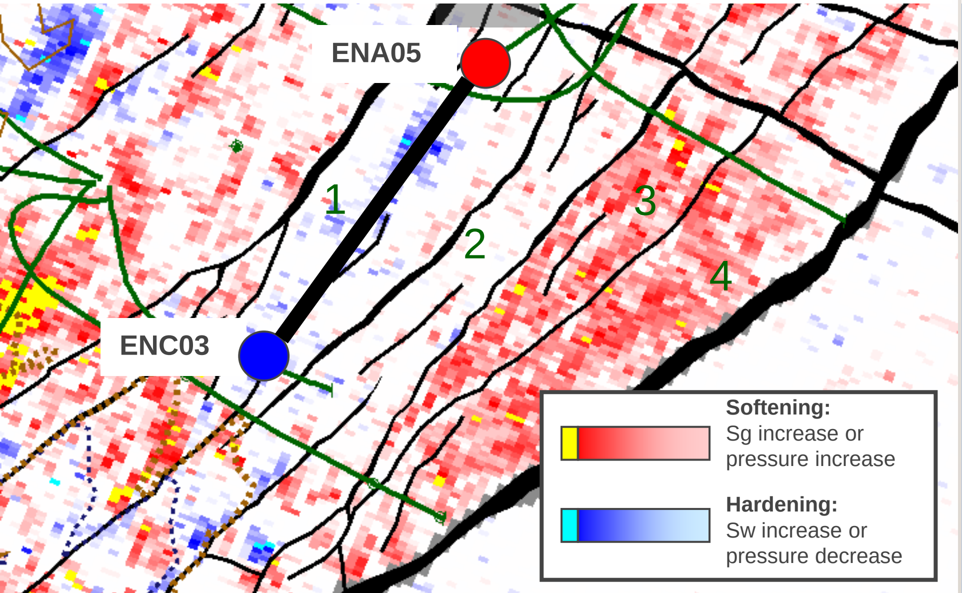
Australia’s first dedicated 4D program

- Acquired and processed for optimum repeatability



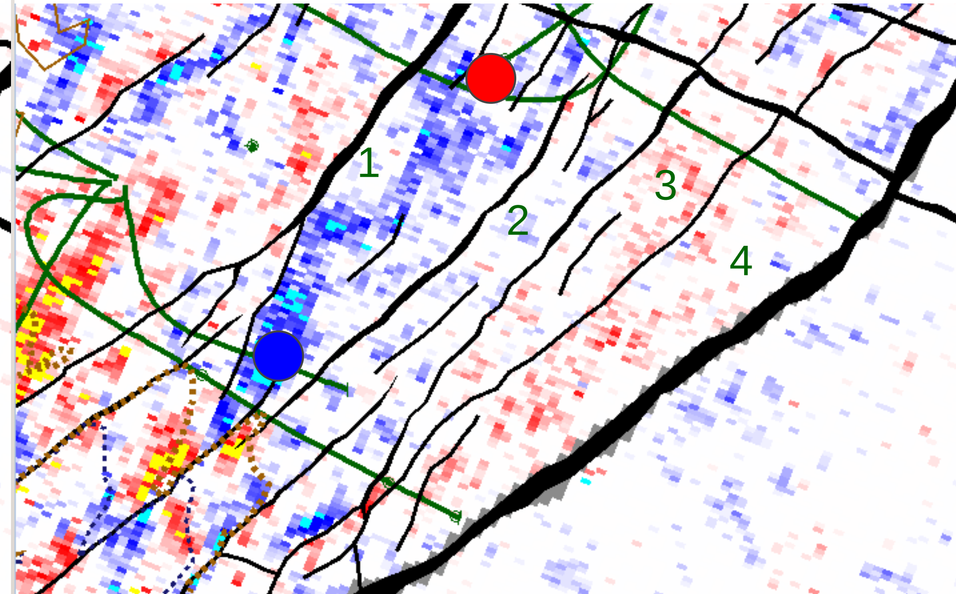
# Sliver South: Monitor 1 4D seismic response

**Monitor 1 – Baseline MIDS difference map**




**MIDS indicate pressure changes**

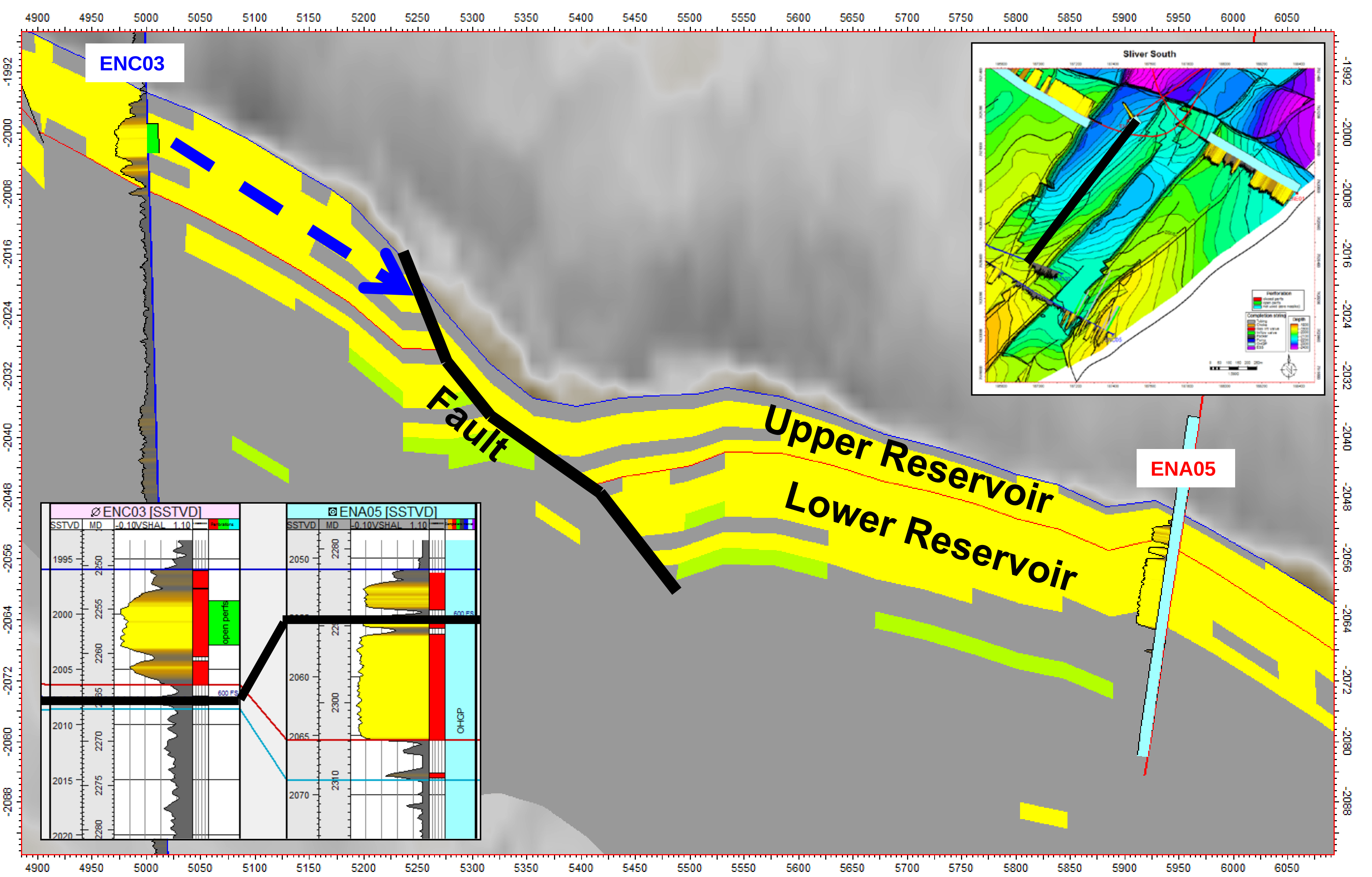
**Monitor 1 – Baseline FARS difference map**



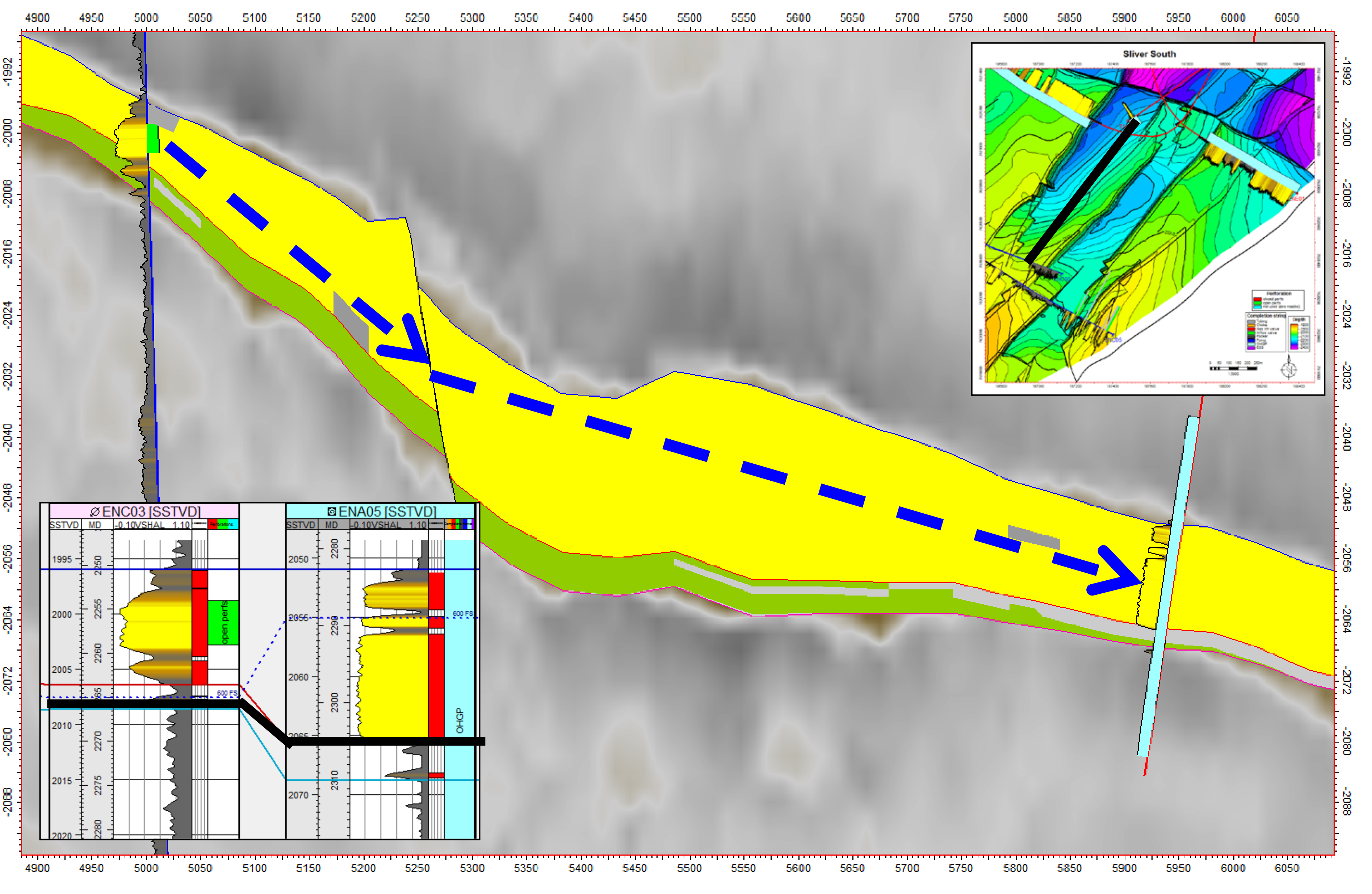

**FARS indicate saturation changes**

- 7 months after field start-up, 4D indicates significant water saturation increase in Segment 1 on FARS
- ENA05 production (early water breakthrough and high water cut) confirms accurate 4D response and likely better than predicted reservoir communication
- 4D seismic response suggests that NE-SW faults are acting as barriers allowing Segments 3 & 4 to pressure up while Segments 1 & 2 are fully swept

# Sliver South: improved geological understanding from 4D seismic and production history



# Sliver South: improved geological understanding from 4D seismic and production history

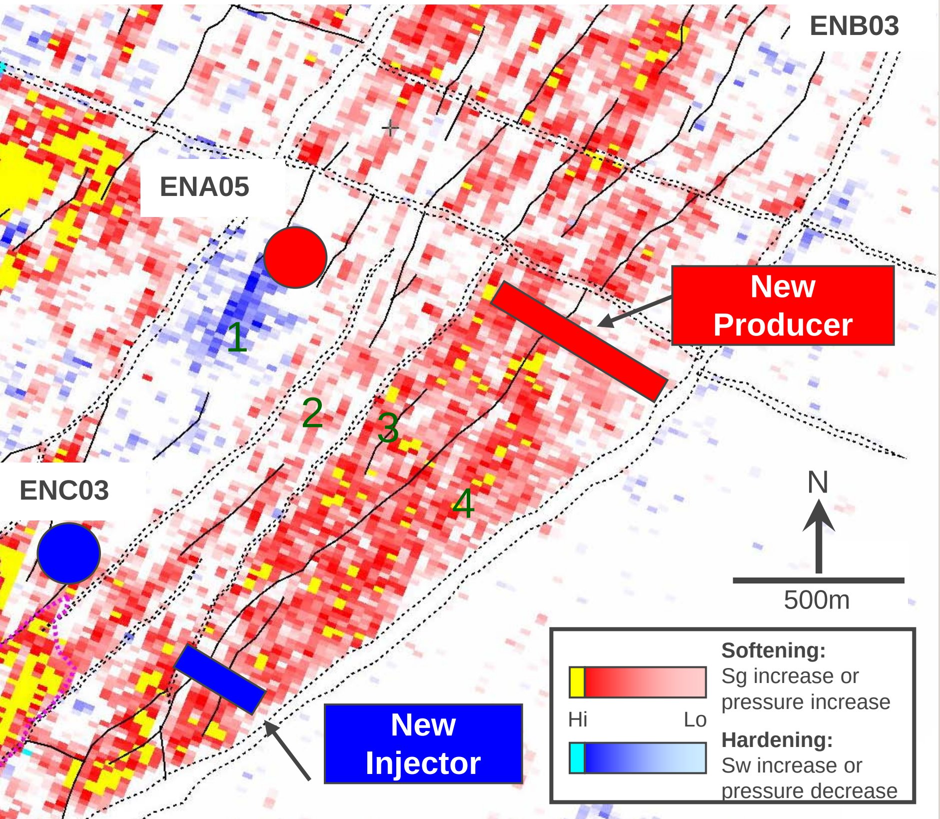


# Aim: Increase in data & knowledge through time

1. Enfield Introduction
2. Exploration/Appraisal Wells (1999-2003)
3. Field Development Plan (2004)
4. Development Drilling (2004-2006)
5. Initial Production Data (mid 2006)
6. 4D Seismic Monitor Surveys (Sept 2007- Dec 2008)
7. Infill Drilling (Mid 2009 & 2010)
8. Conclusions

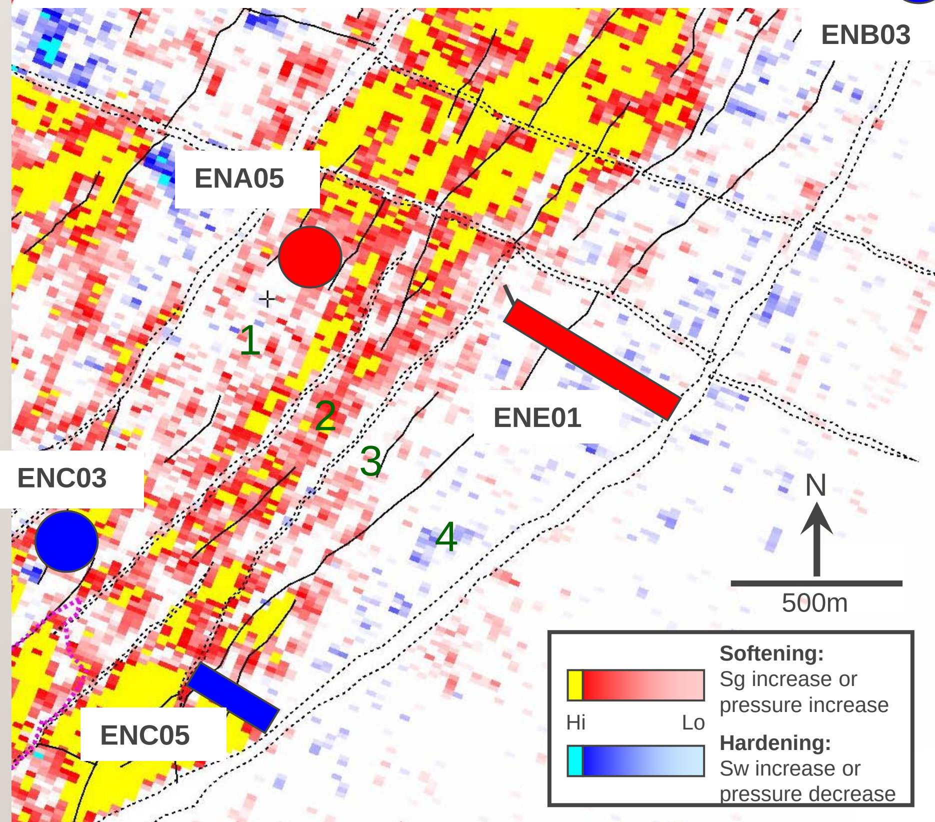
# Sliver South Segments 3 & 4 Monitors 2 & 3 4D seismic response

**Monitor 2 – Baseline MIDS difference map**




**MIDS indicate pressure changes**

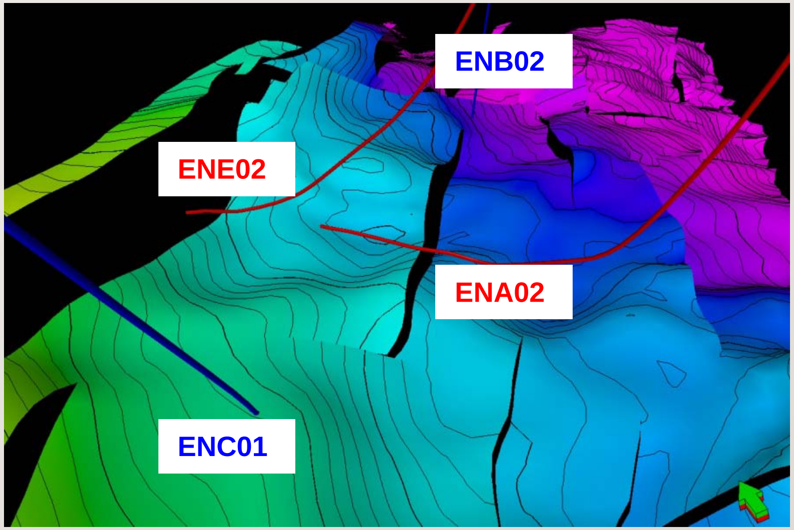
**Monitor 3 – Baseline MIDS difference map**



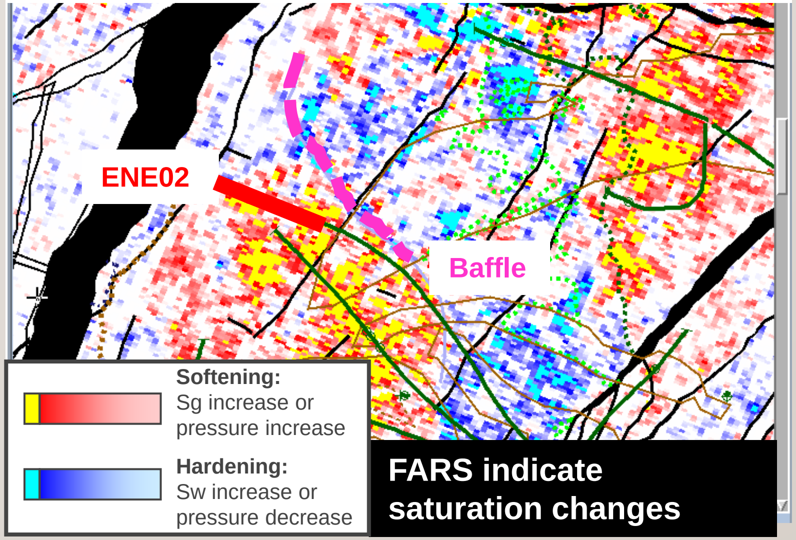

**MIDS indicate pressure changes**

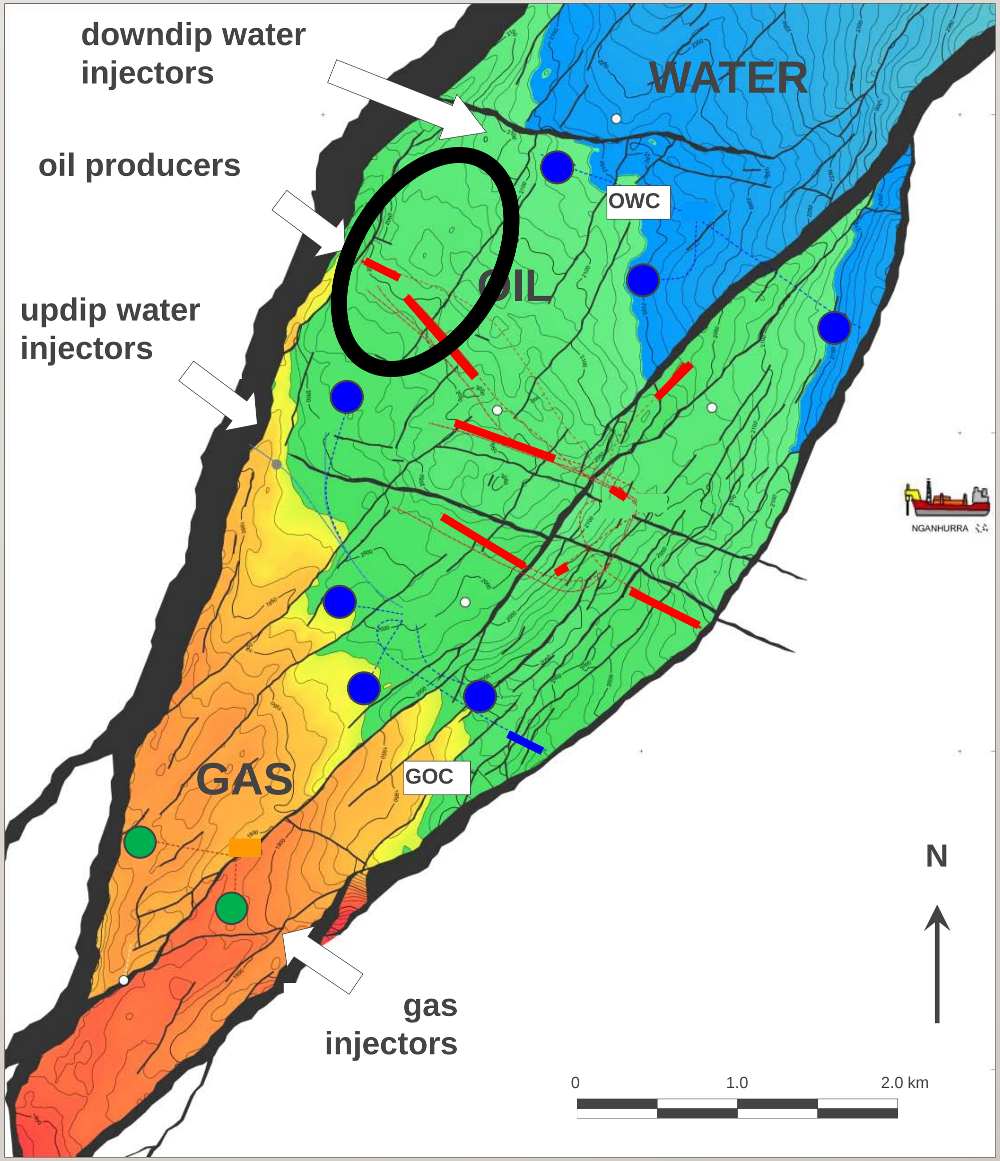
- Monitor 2 survey indicates Segments 3 & 4 highly pressured-up
- New producer-injector pair form main component of infill drilling campaign
- Monitor 3 shows Segments 3 & 4 swept by new well: excellent communication

# Main West infill well

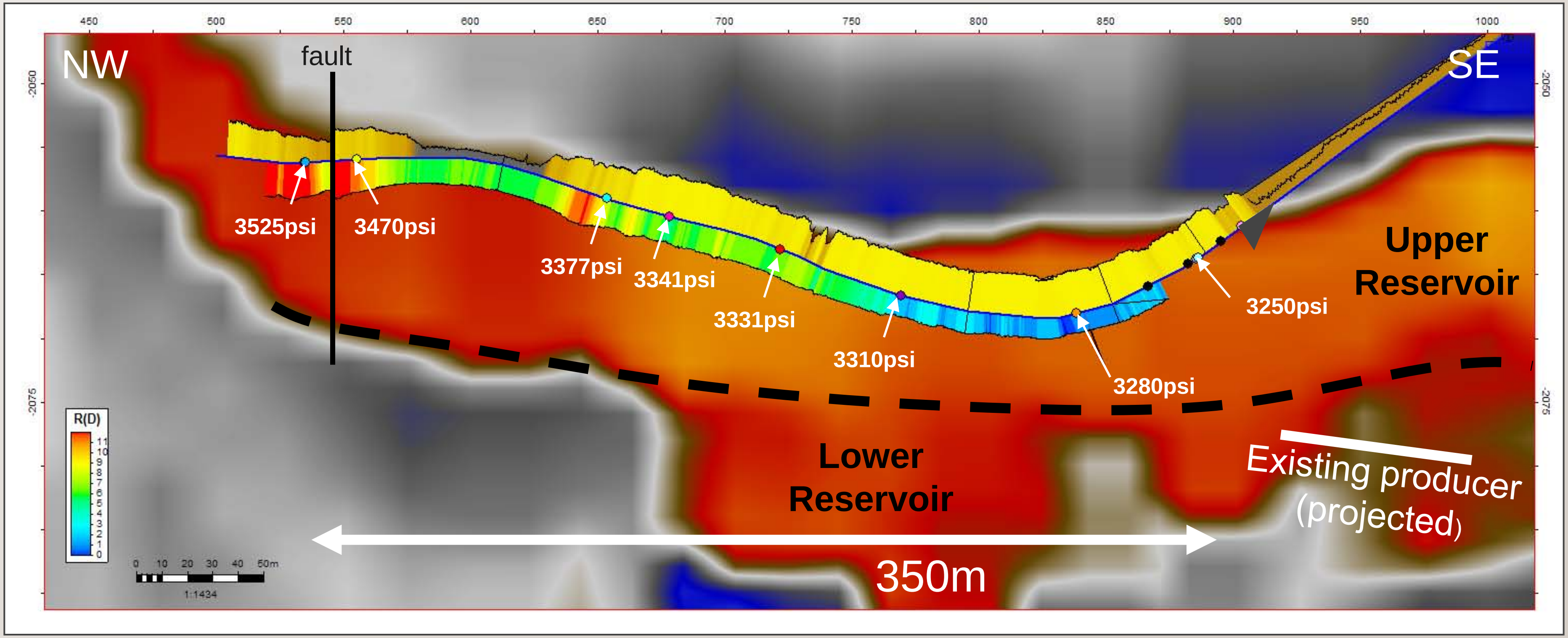



**Monitor 2 – Baseline FARS difference map**



# Main West well result

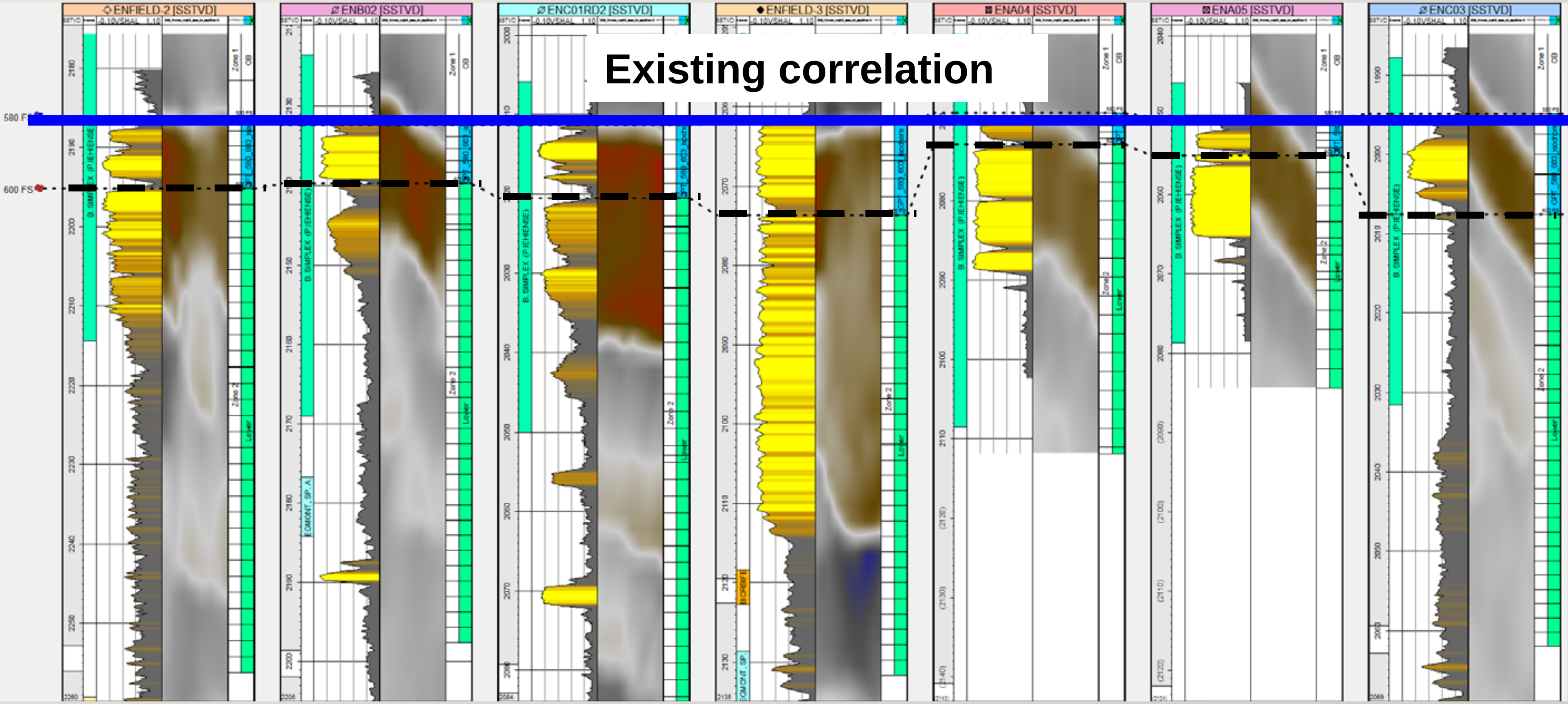



- resistivity logs indicate gradation in water saturation from heel to toe
- reservoir pressures demonstrate dynamic behaviour as well moves away from location of existing producer
- conclusion: ENE02 and ENA02 reservoirs in communication
- tank-like behaviour and larger connected volume in main west area
- reservoir is more efficiently drained by new well

# Aim: Increase in data & knowledge through time

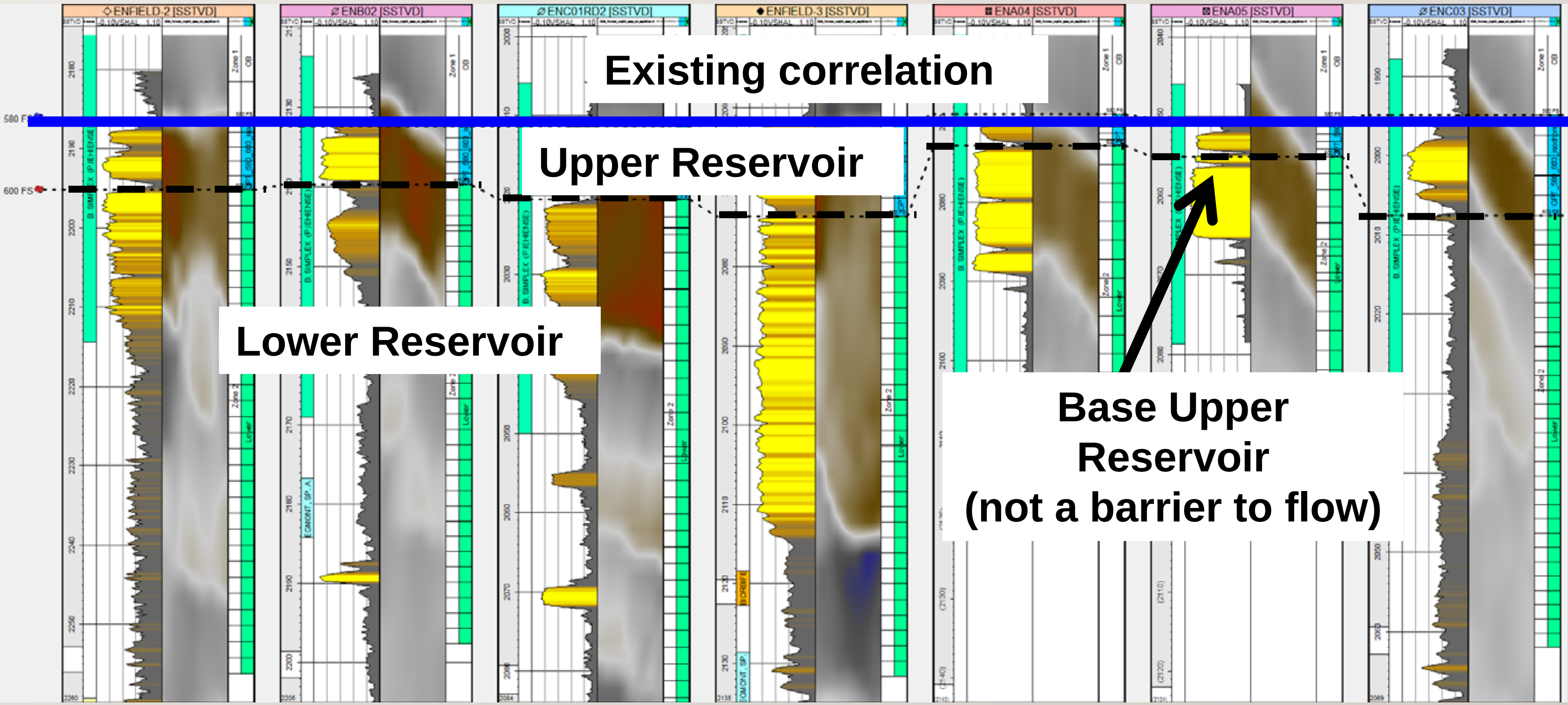
1. Enfield Introduction
2. Exploration/Appraisal Wells (1999-2003)
3. Field Development Plan (2004)
4. Development Drilling (2004-2006)
5. Initial Production Data (mid 2006)
6. 4D Seismic Monitor Surveys (Sept 2007- Dec 2008)
7. Infill Drilling (Mid 2009 & 2010)
8. Updated conceptual geological model
9. Conclusions

# Stratigraphic correlation



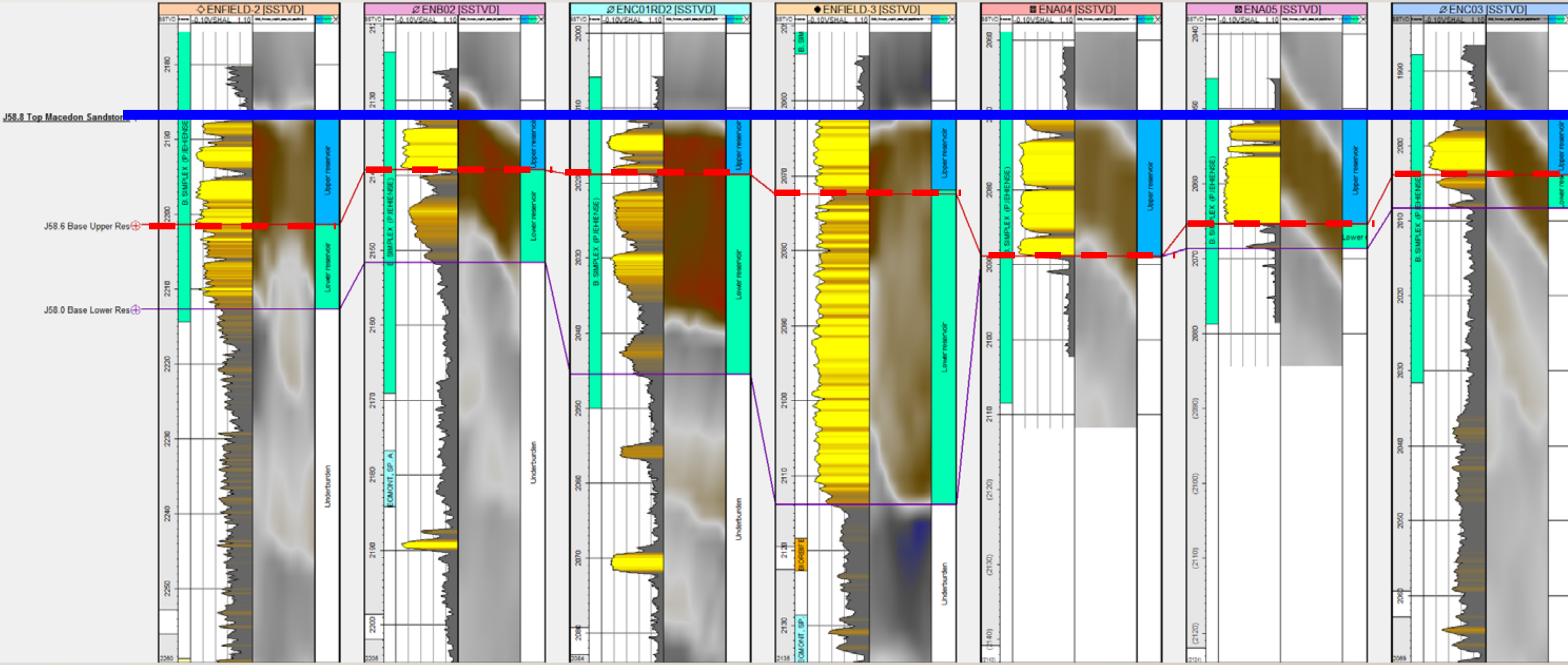

- No evidence of field-wide flooding surface/vertical baffle
- Field connectivity and performance is generally better than old model predicted.
- Model needs to be both geologically valid and match actual field behaviour

# Stratigraphic correlation



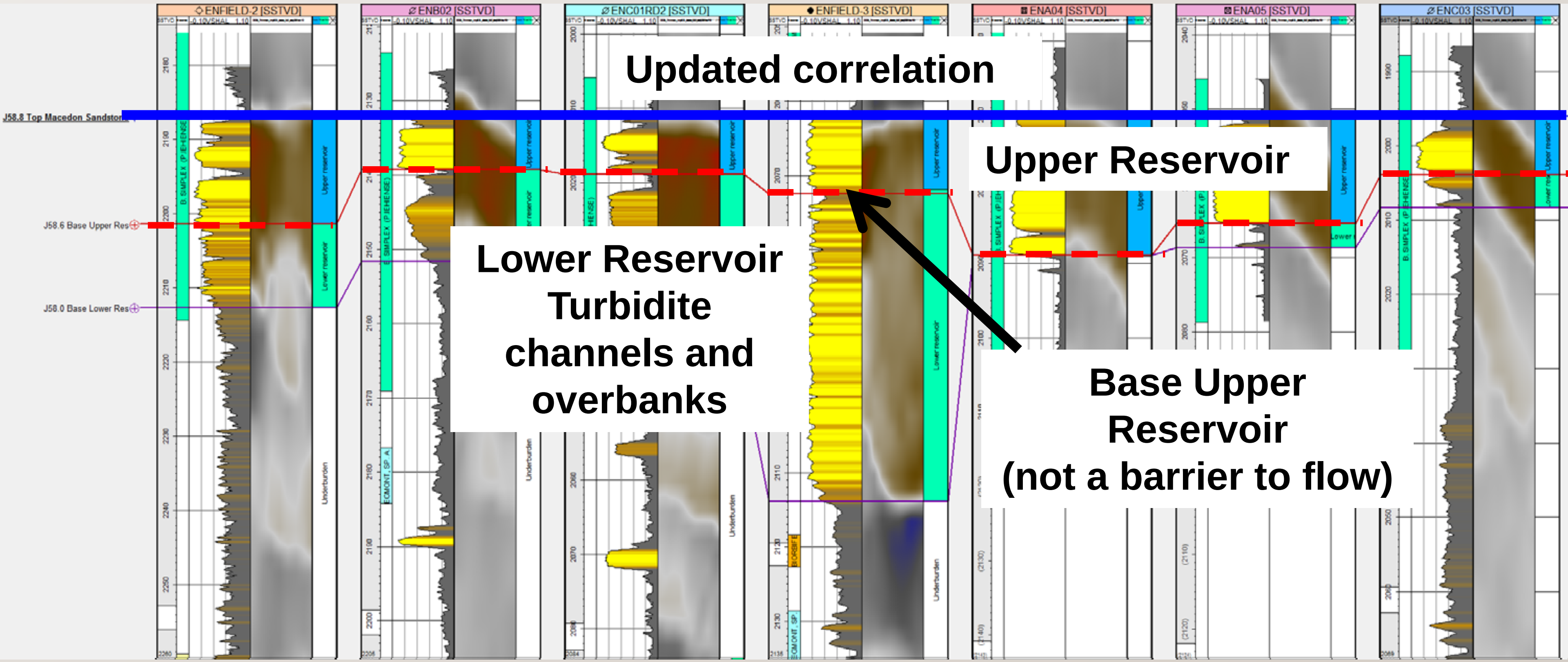

- No evidence of field-wide flooding surface/vertical baffle
- Field connectivity and performance is generally better than old model predicted.
- Model needs to be both geologically valid and match actual field behaviour

# Stratigraphic correlation




- No evidence of field-wide flooding surface/vertical baffle
- Field connectivity and performance is generally better than old model predicted.
- Model needs to be both geologically valid and match actual field behaviour

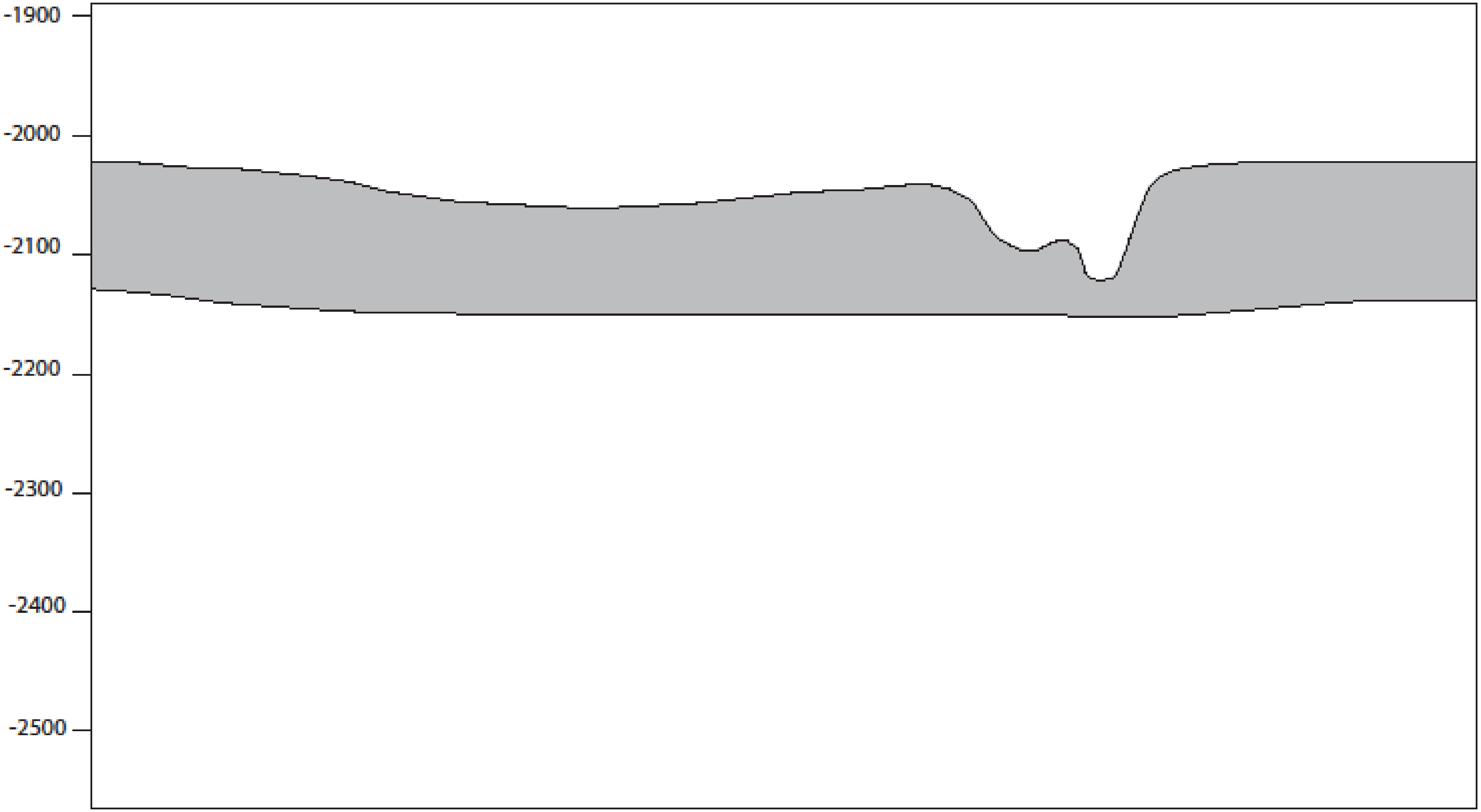
# Stratigraphic correlation




- No evidence of field-wide flooding surface/vertical baffle
- Field connectivity and performance is generally better than old model predicted.
- Model needs to be both geologically valid and match actual field behaviour

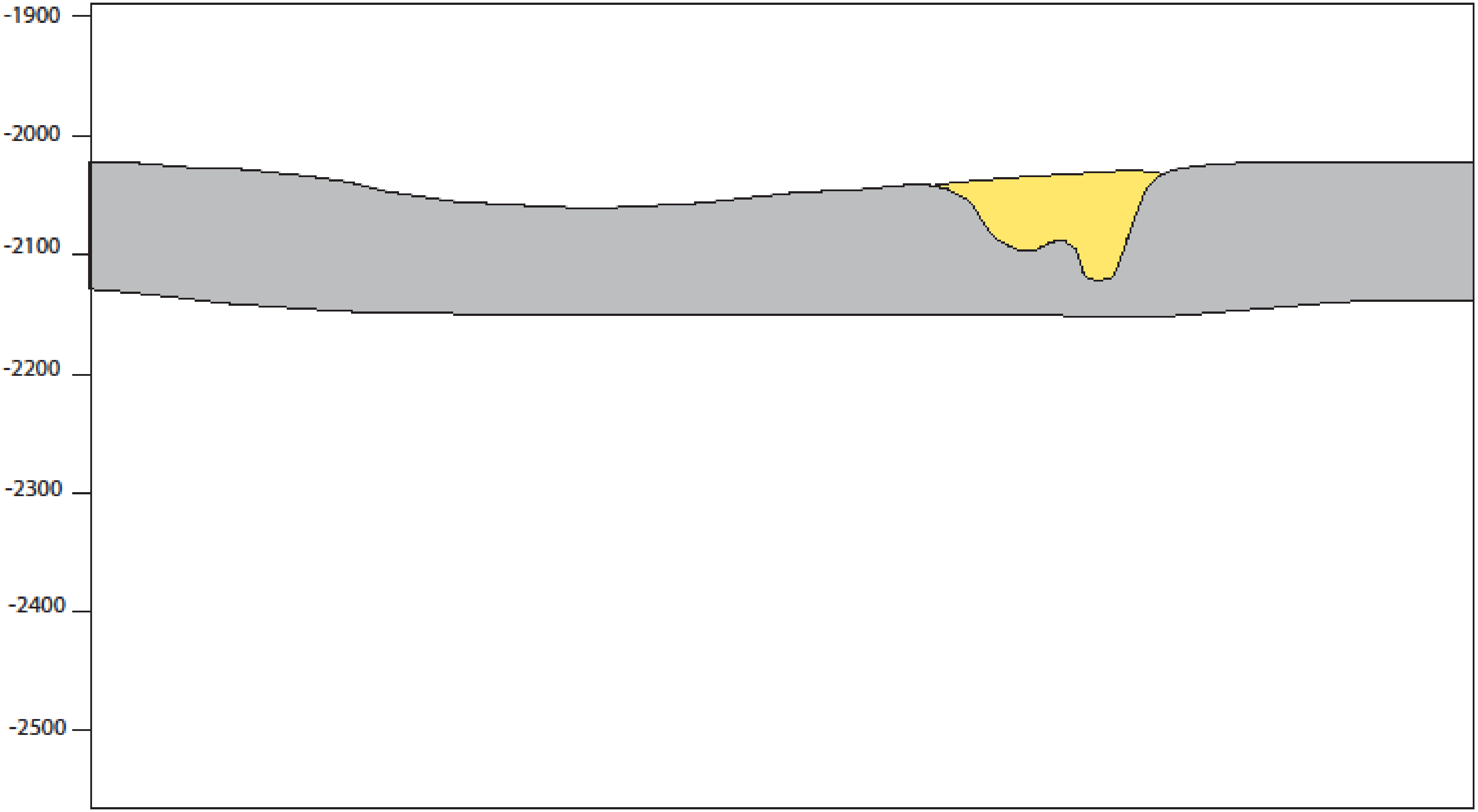
# Enfield conceptual geological model

1. Turbidite channels erode marine shale at Enfield.



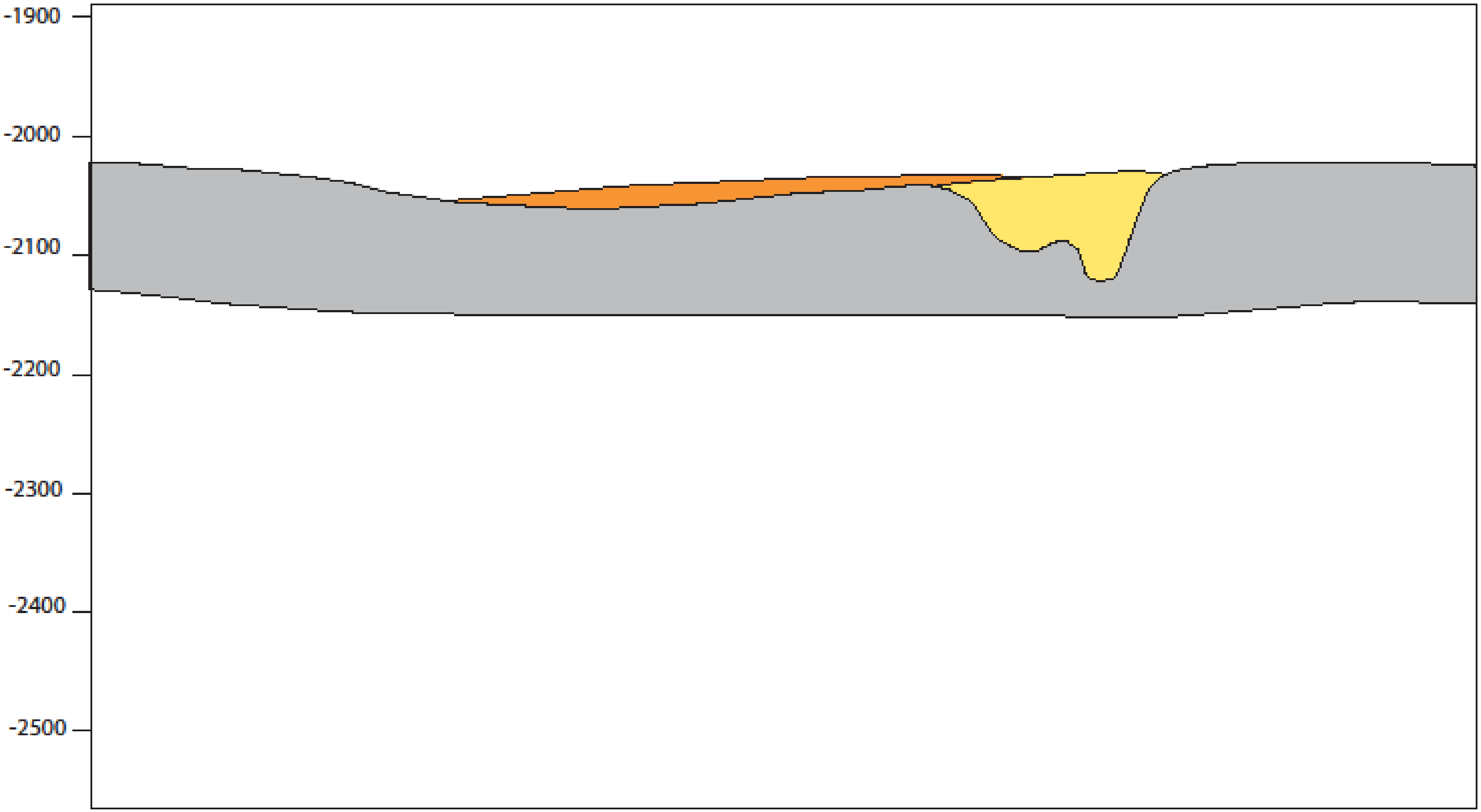
# Enfield conceptual geological model

2. Lower Reservoir deposited in confined channels.



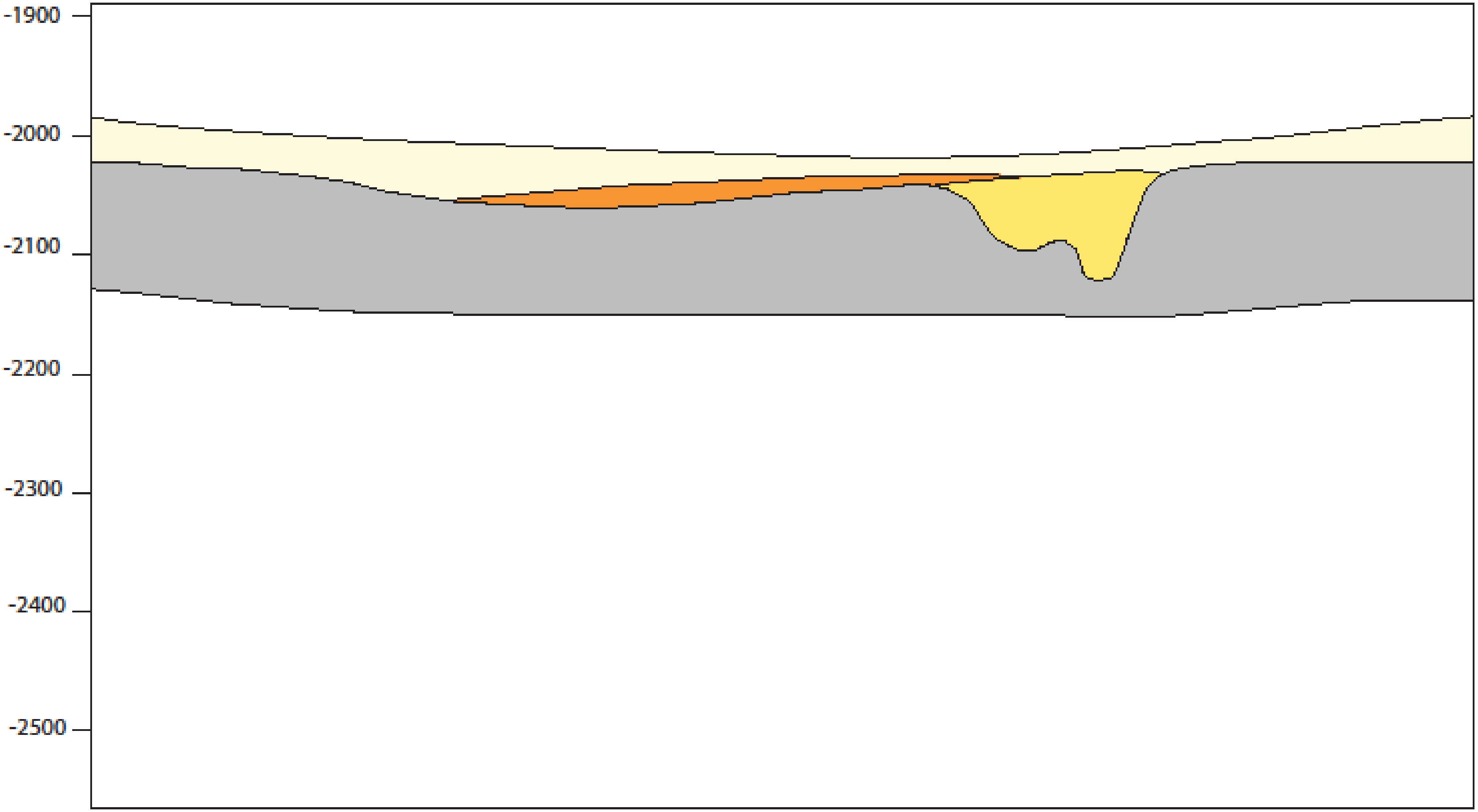
# Enfield conceptual geological model

3. Channels filled; overbank facies deposited on channel margins, preferentially on the outer banks.



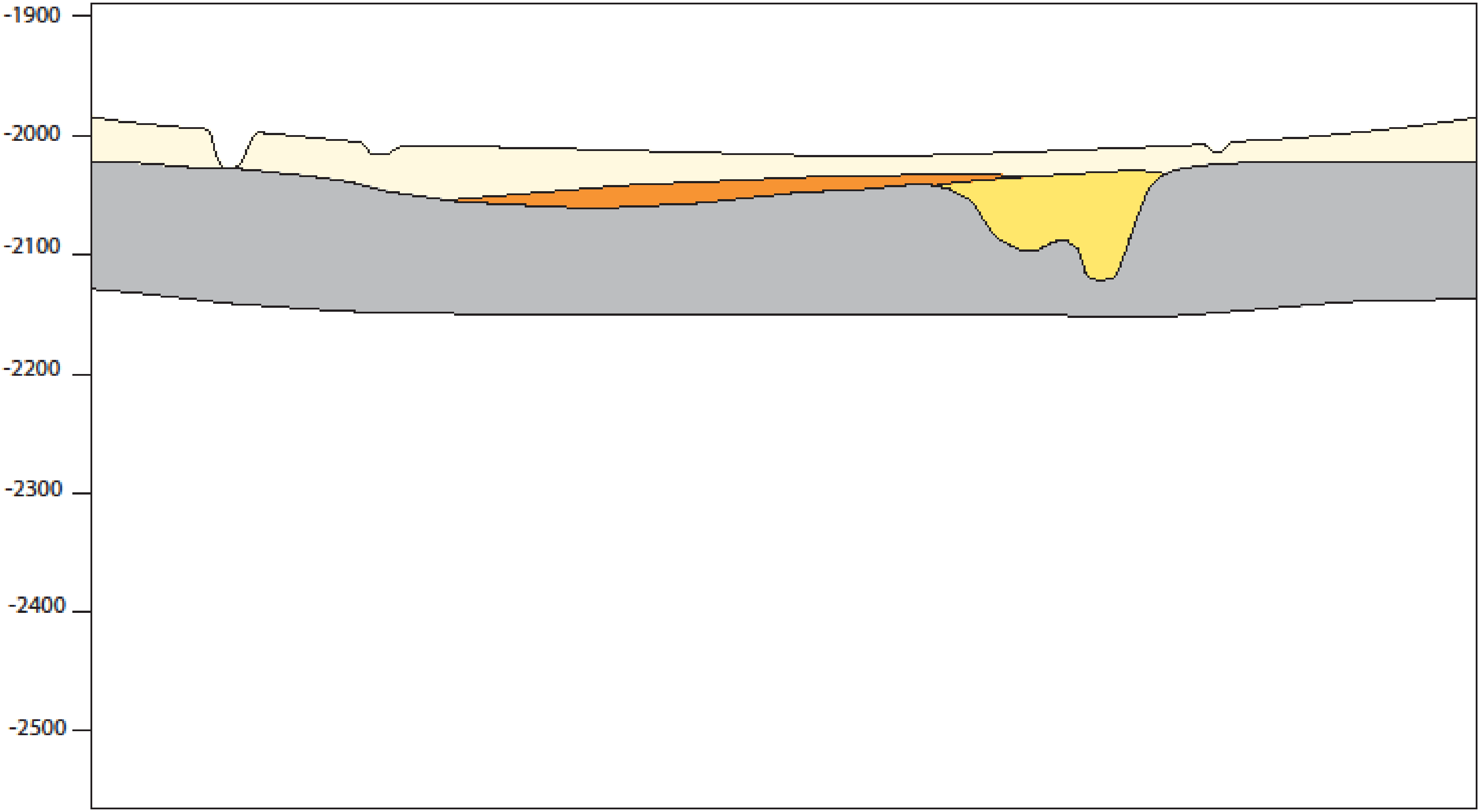
# Enfield conceptual geological model

4. A second series of channels is preferentially deposited in topographic lows resulting in an amalgamated sheet sand (Upper Reservoir).



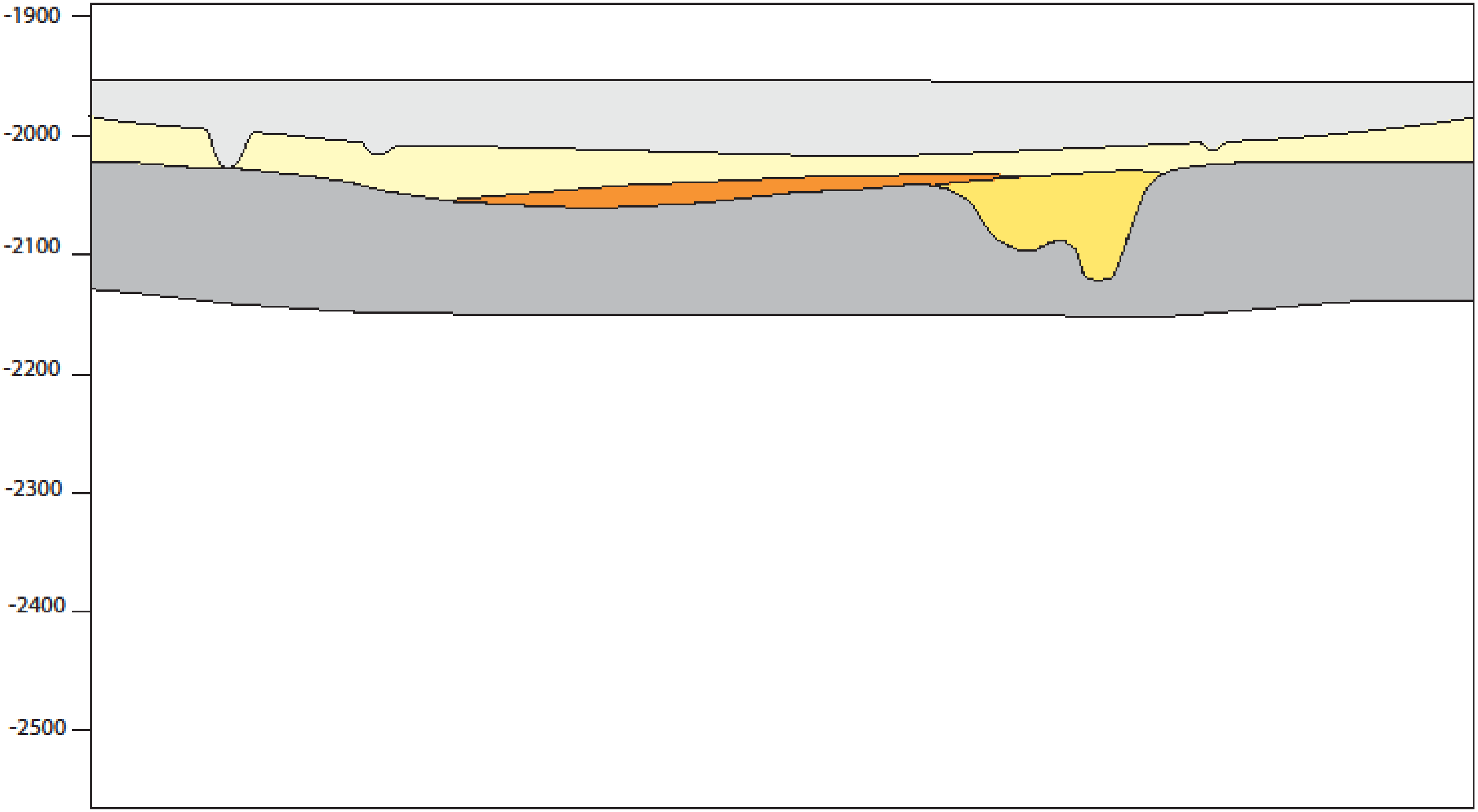
# Enfield conceptual geological model

5. Late-stage channels erode into the Upper Reservoir.



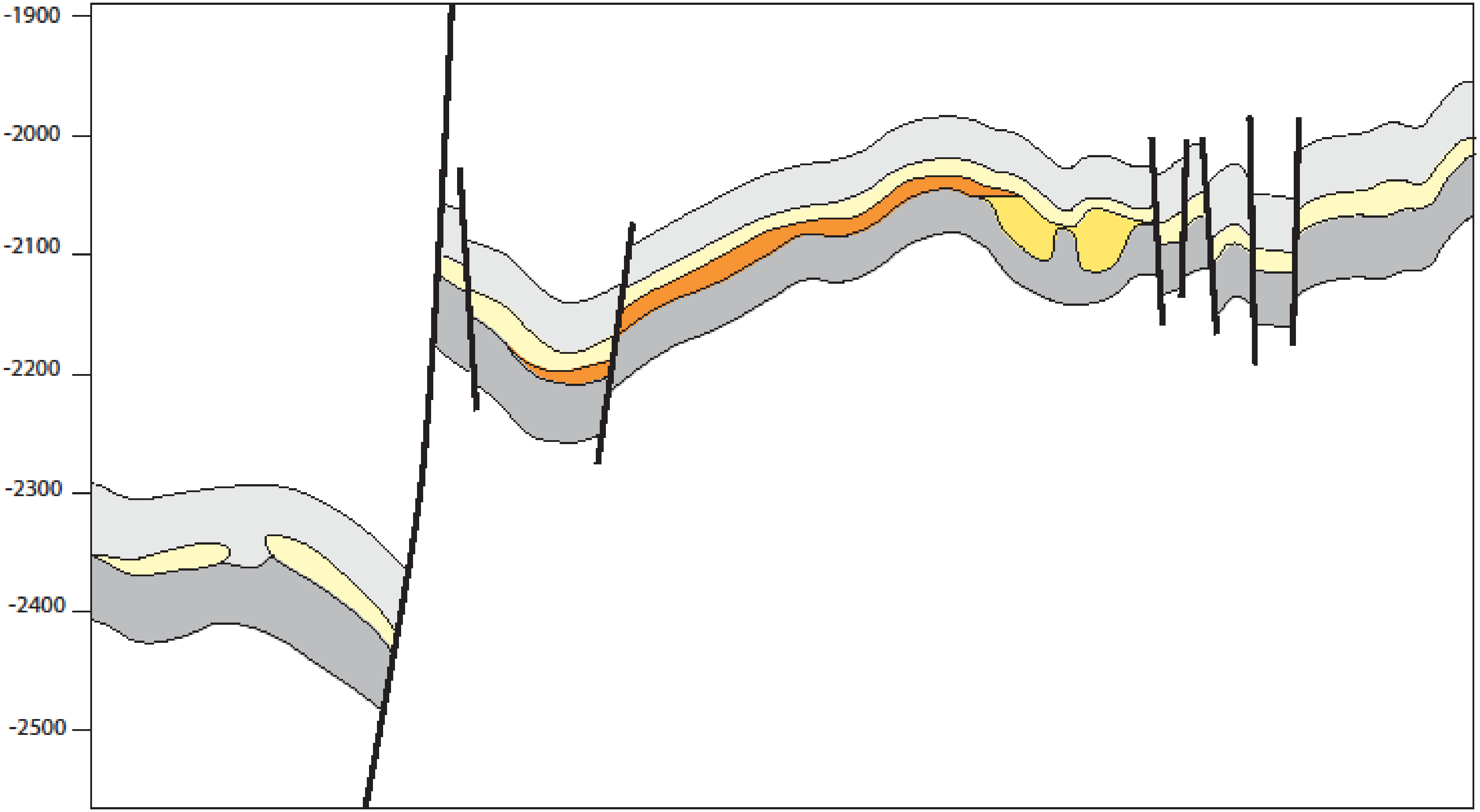
# Enfield conceptual geological model

6. Marine shale deposited.

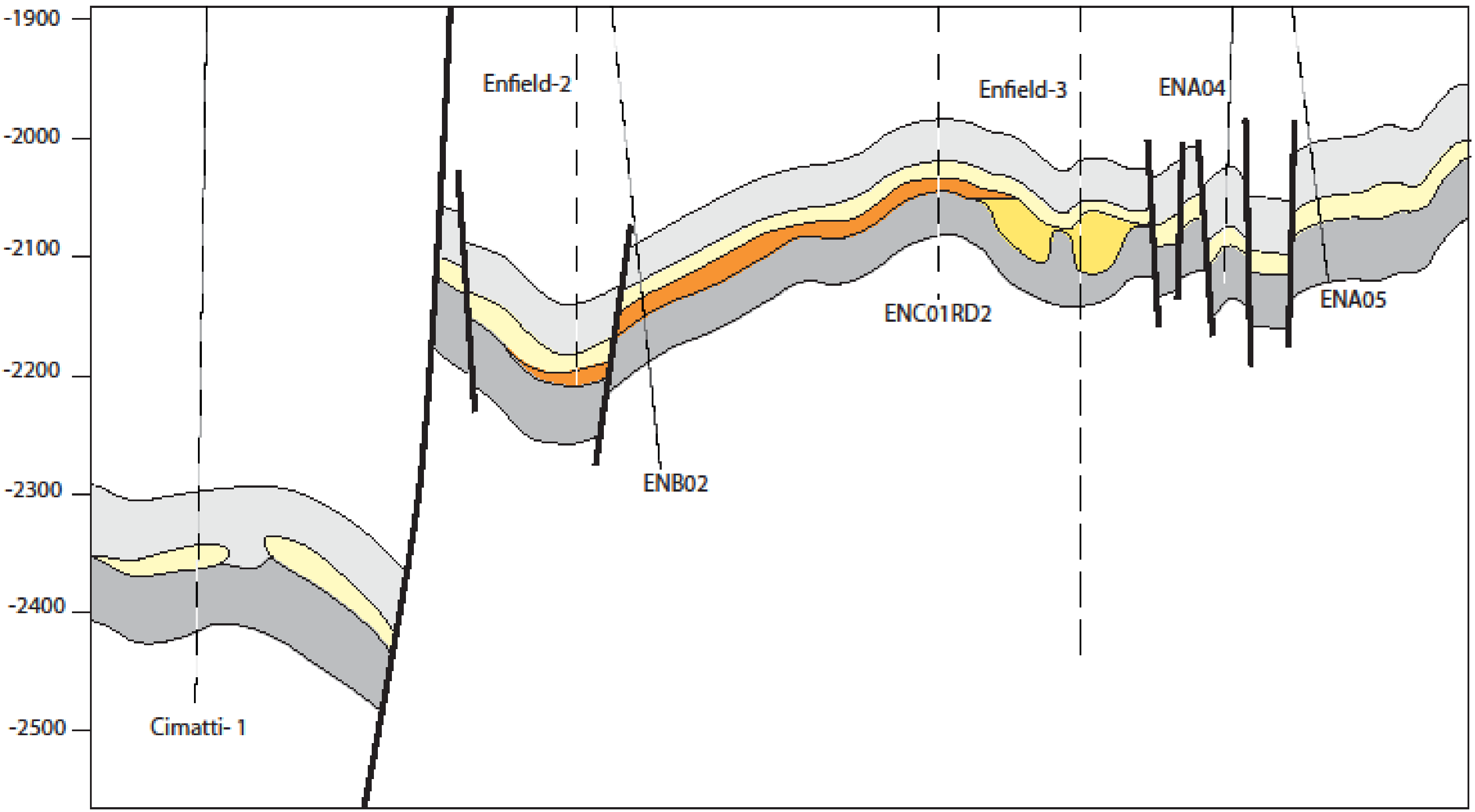


# Enfield conceptual geological model

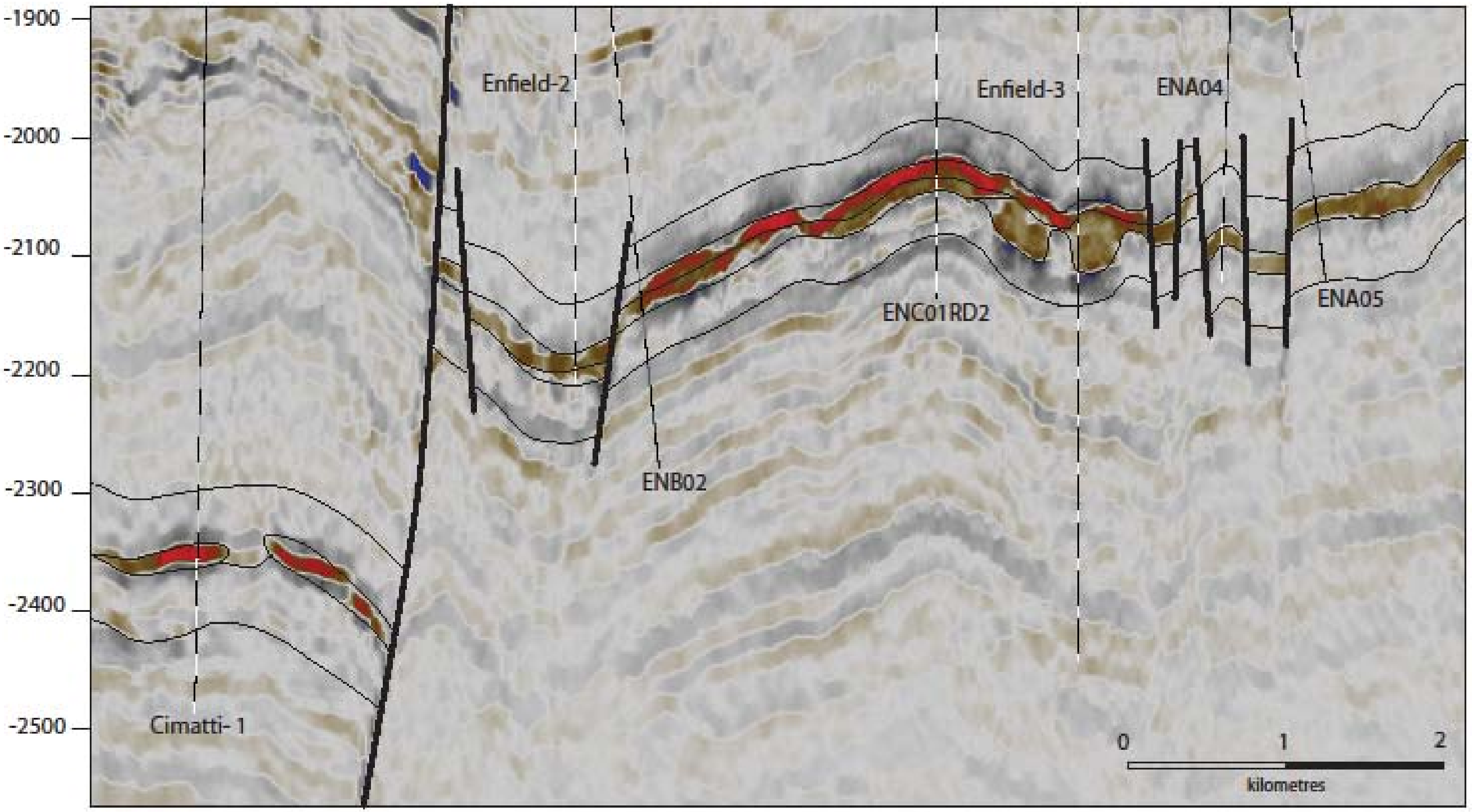
7. Faulting occurs, compartmentalising Enfield.



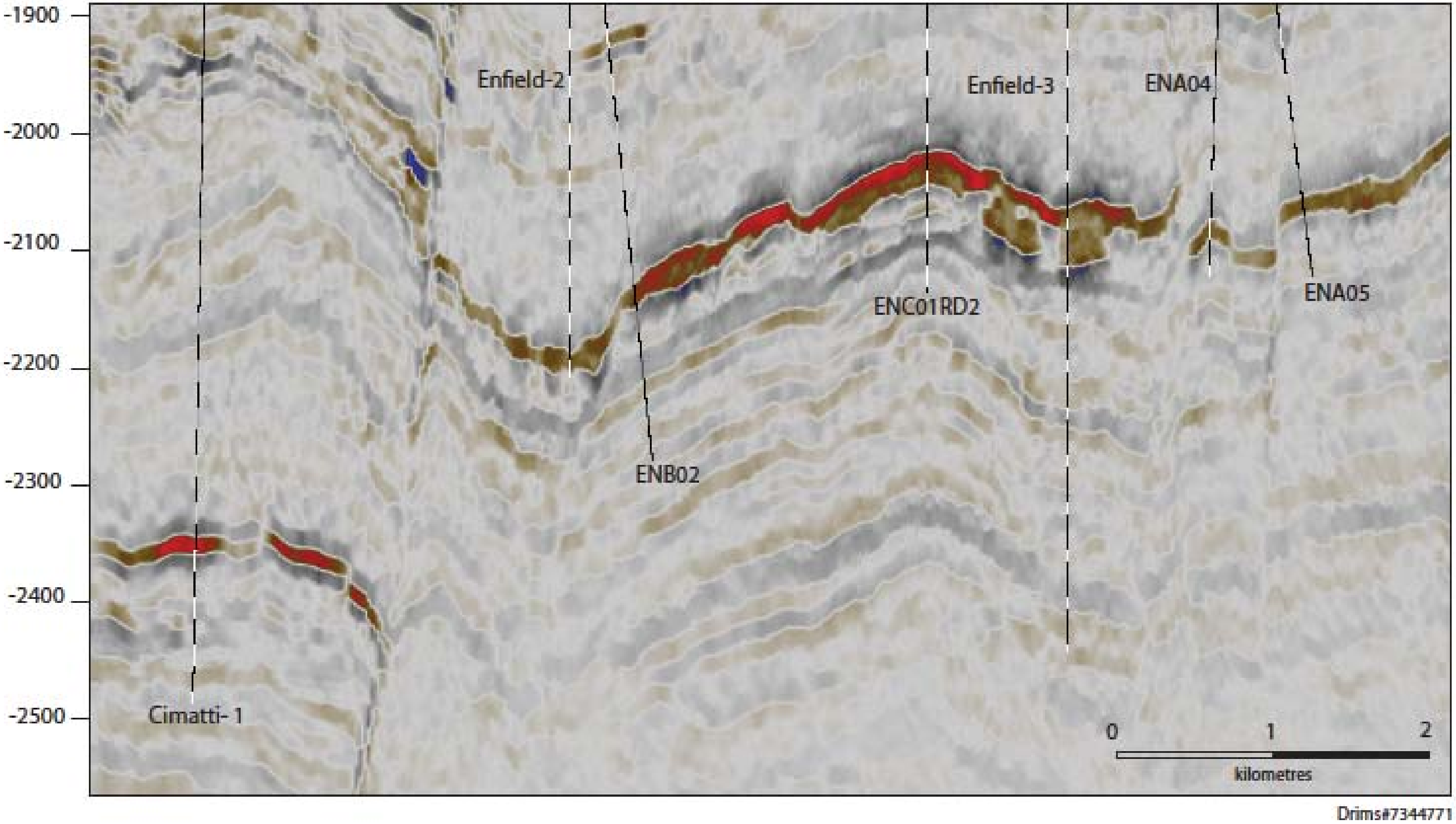
# Enfield conceptual geological model



# Enfield conceptual geological model



# Enfield conceptual geological model



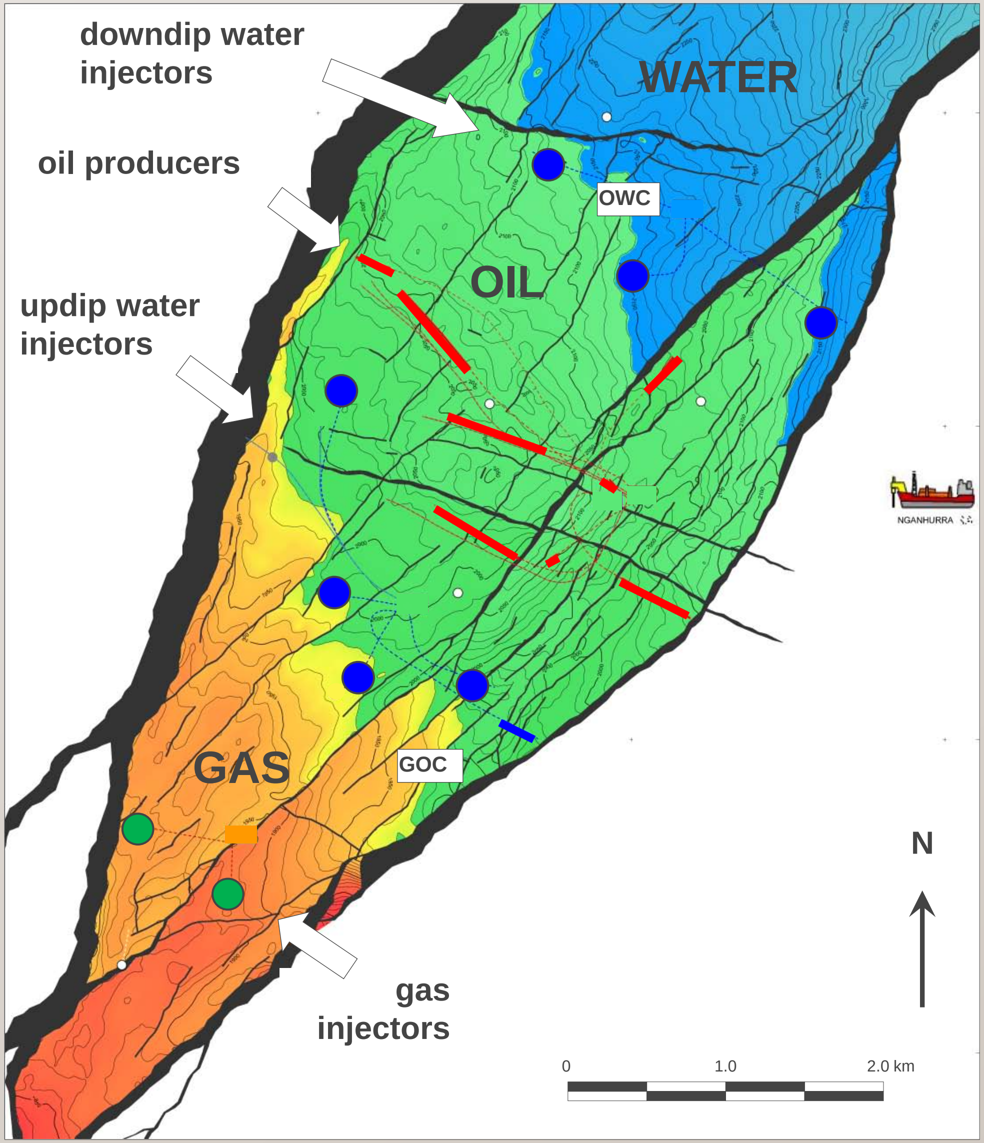
# Conclusions

- always re-assess the geological model as new data comes to light

- integrate dynamic data: 4D seismic, well results, production history

- a model that is both geologically valid and matches dynamic field behaviour gives confidence in its predictive power

- Updated geological model used to
    - predict remaining reserves
    - optimise production
    - identify new infill well opportunities



# Acknowledgements


- Woodside Energy Ltd and Mitsui E & P Australia Pty Ltd, holders of the Enfield production licence
- Vaughan Cutten
- The Enfield Development Team