Impact of Heterogeneity on Flow in Shallow-Marine Reservoirs: Application to a Thin Oil Column Produced via Horizontal Wells*

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Abstract

Numerous studies have demonstrated that heterogeneity in shallow-marine reservoirs can have a significant impact on flow. However, most of these focus on oil recovery by water injection via vertical producer and injector wells. Yet the impact of heterogeneity on flow depends also on the fluid properties, flow rates and principal flow direction. The aim of this study is to quantify the impact of heterogeneity on flow in a shallow marine reservoir that hosts a thin oil rim (Troll Field, North Sea), overlain by a large gas cap and underlain by an active aquifer, with oil produced via long horizontal wells.

In the sector of interest, the reservoir comprises a series of stacked parasequences that each coarsens upwards from micaceous, silty, fine-grained sandstone at the base (10's-100's mD, termed M-sands) to clean, coarse-grained sandstone at the top (100's-1000's mD, termed C-sands). A sector model, measuring 3200 m x 750 m x 150 m and containing a single horizontal well, was taken from a full field geological model, and downscaled onto a highly refined grid to capture flow. Parasequence-bounding flooding surfaces and intra-parasequence clinoforms are associated with zones of calcite cement; these are not included in the full field model and were added to the sector model using an in-house algorithm.

The most significant heterogeneity that impacts on oil production is the permeability contrast between C- and M-sands. A higher contrast reduces the pressure drawdown into the C-sands, delaying gas breakthrough and yielding higher recovery. The next most significant heterogeneity is the presence of stratabound calcite cements along clinoforms; similar cements along flooding surfaces have a much lower ranking. Cements along clinoforms reduce cumulative oil production because they cause oil to be bypassed and channel gas into the well completions; they do not 'hold back' the encroaching gas. Uncertainty in the kv/kh ratio of the sands, which reflects bed-scale heterogeneity, has only a small impact on oil recovery because flow is primarily through the high permeability C-sands.

The results presented here are often counter-intuitive, and contrast with those obtained from waterflood simulations with vertical wells. They provide insight that can be used to guide model construction and history matching. Moreover, they demonstrate that clinoforms can have a large impact on production, even though these features are typically neglected in geocellular models of shallow-marine reservoirs.

References Cited

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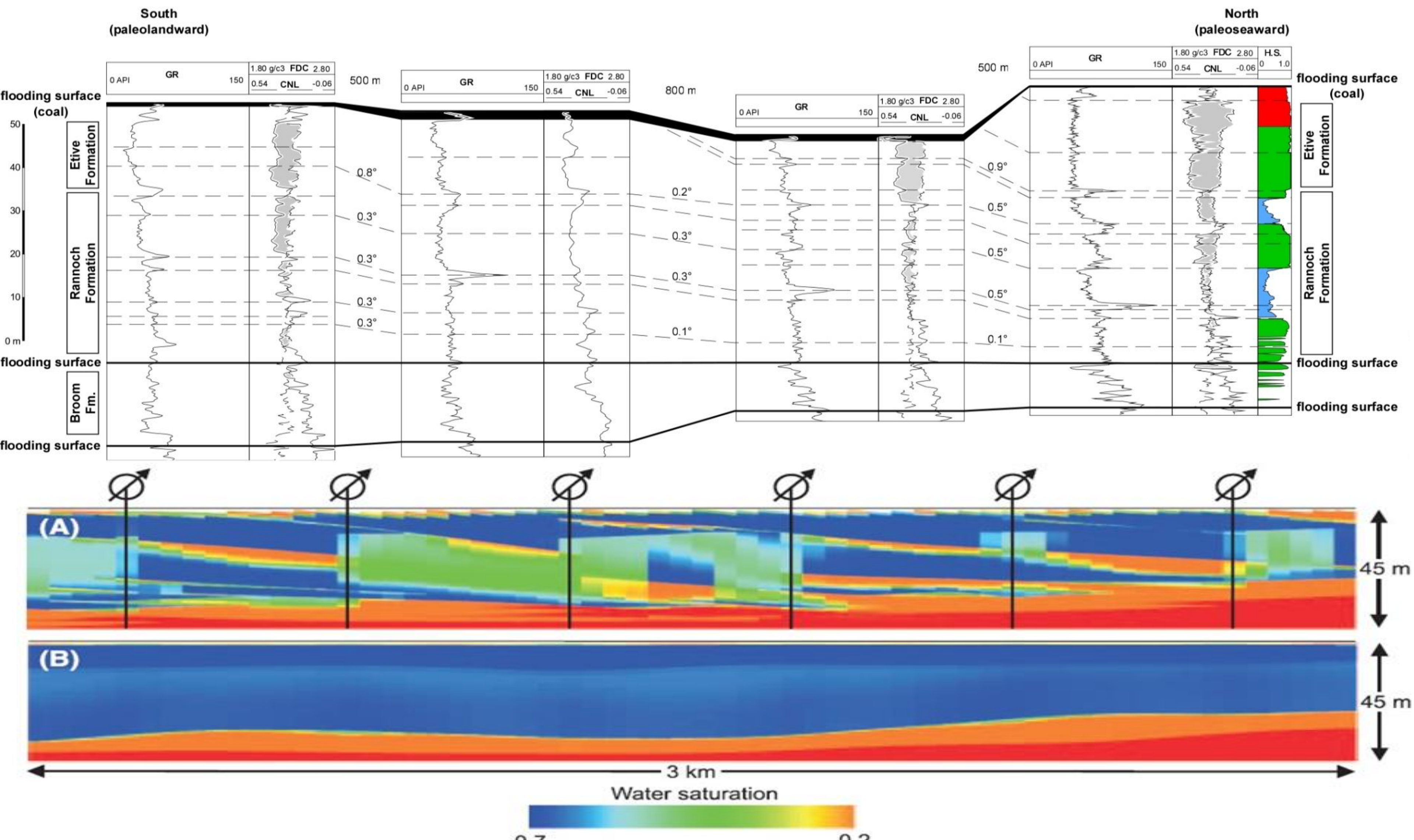
- Schlumberger for providing the ECLIPSE® reservoir simulation software.

Motivation: Impact of clinoforms on sweep in the Brent Field



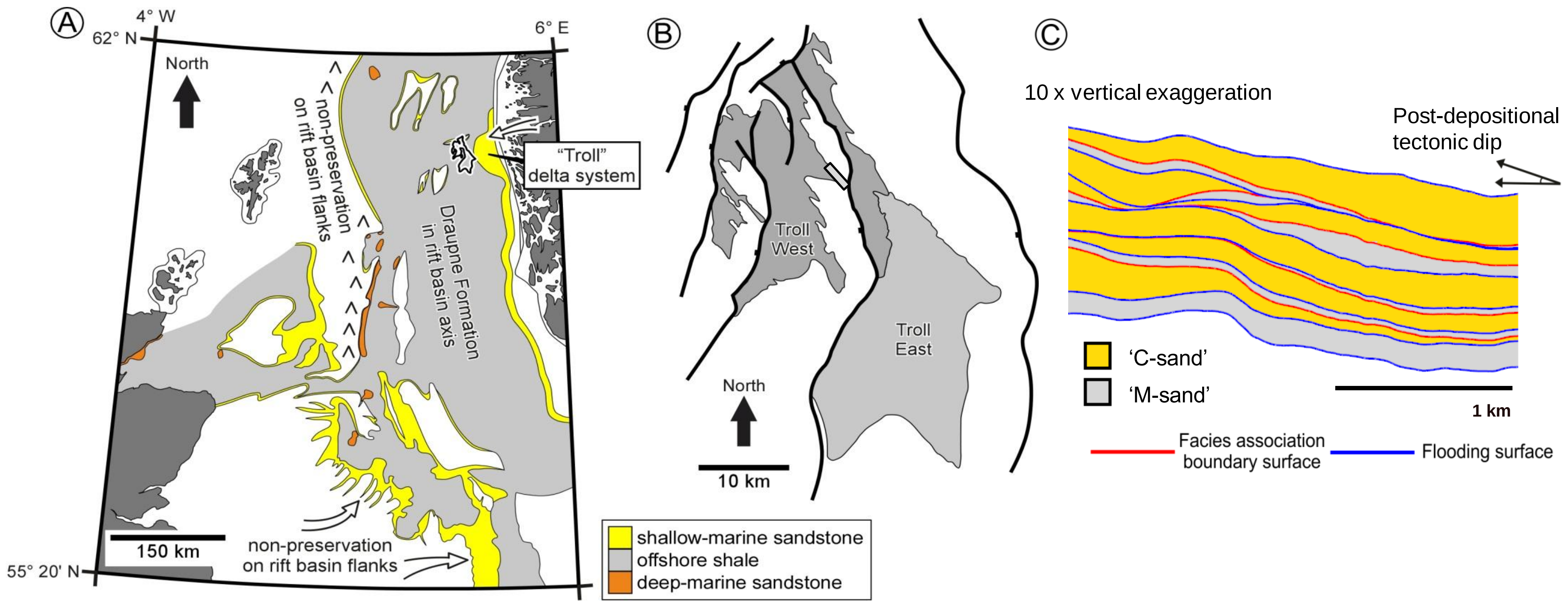
Jackson et al. (2009)

Aims of study

- Quantify the impact of heterogeneity on flow in a shallow marine reservoir that hosts a thin oil rim, overlain by a gas cap and underlain by an aquifer, with oil production via horizontal wells.

- Application to a high resolution model of the Jurassic Sognefjord Formation, in a fault bounded sector of the Troll Field, offshore Norway.

Geological setting

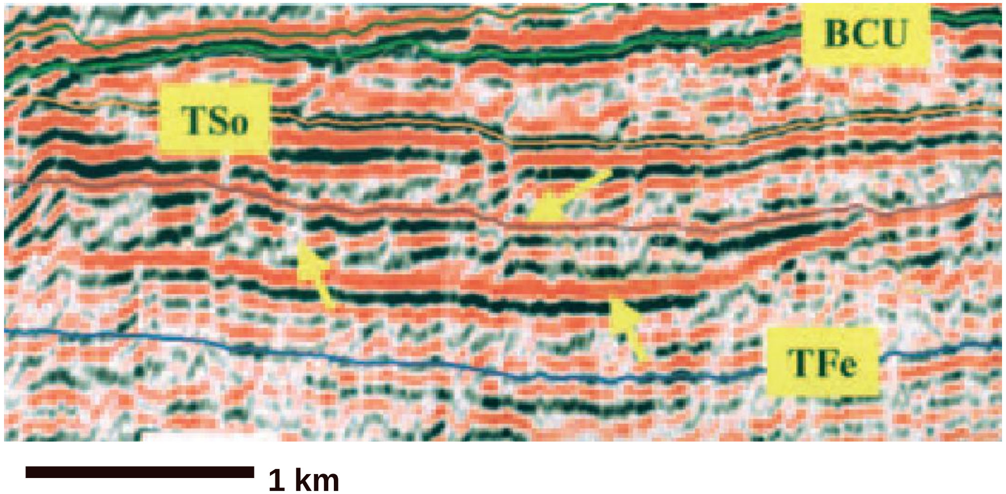


Graham *et al.*, In Review

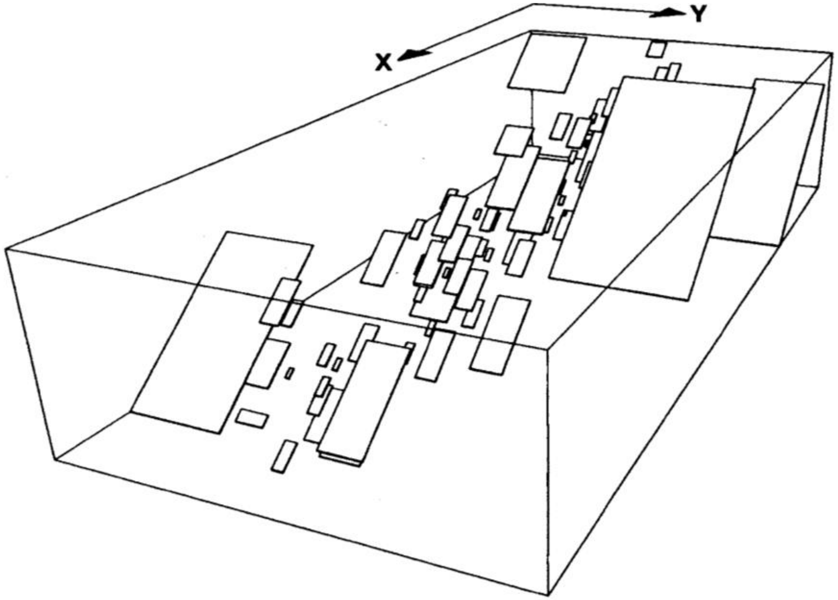
- ❑ Sandstone reservoir, deposited in a shallow-marine environment
- ❑ Series of stacked parasequences: coarsens upwards, from micaceous, silty, fine-grained sandstone (termed 'M-sands'), to clean, coarser-grained sandstone (termed 'C-sands')

Calcite cement along clinoforms in the Troll Field

3x vertical exaggeration

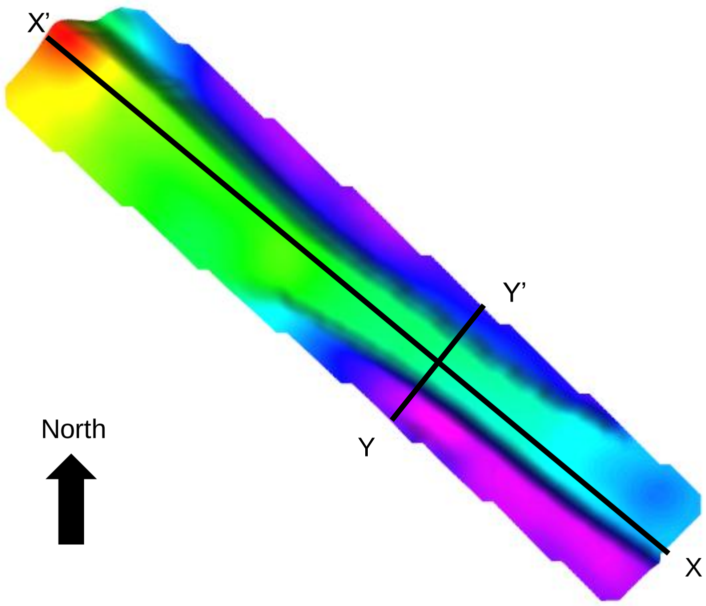


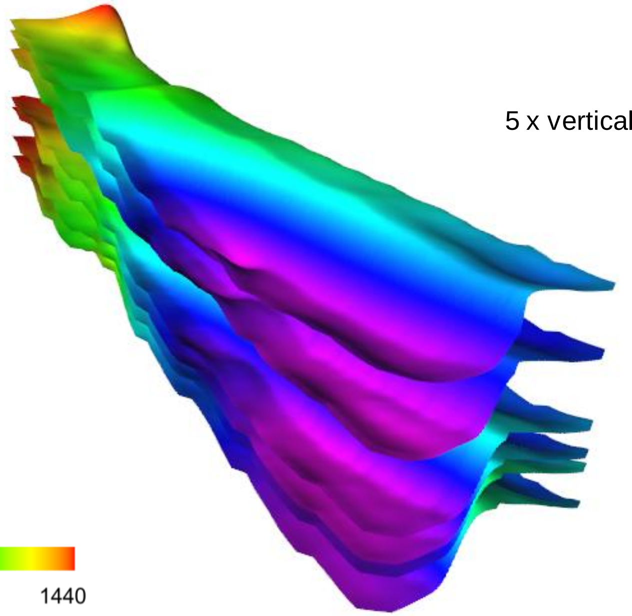
Dreyer *et al*. (2005)



Lien *et al. (*1992)

Stratigraphy, faults and facies from full-field model

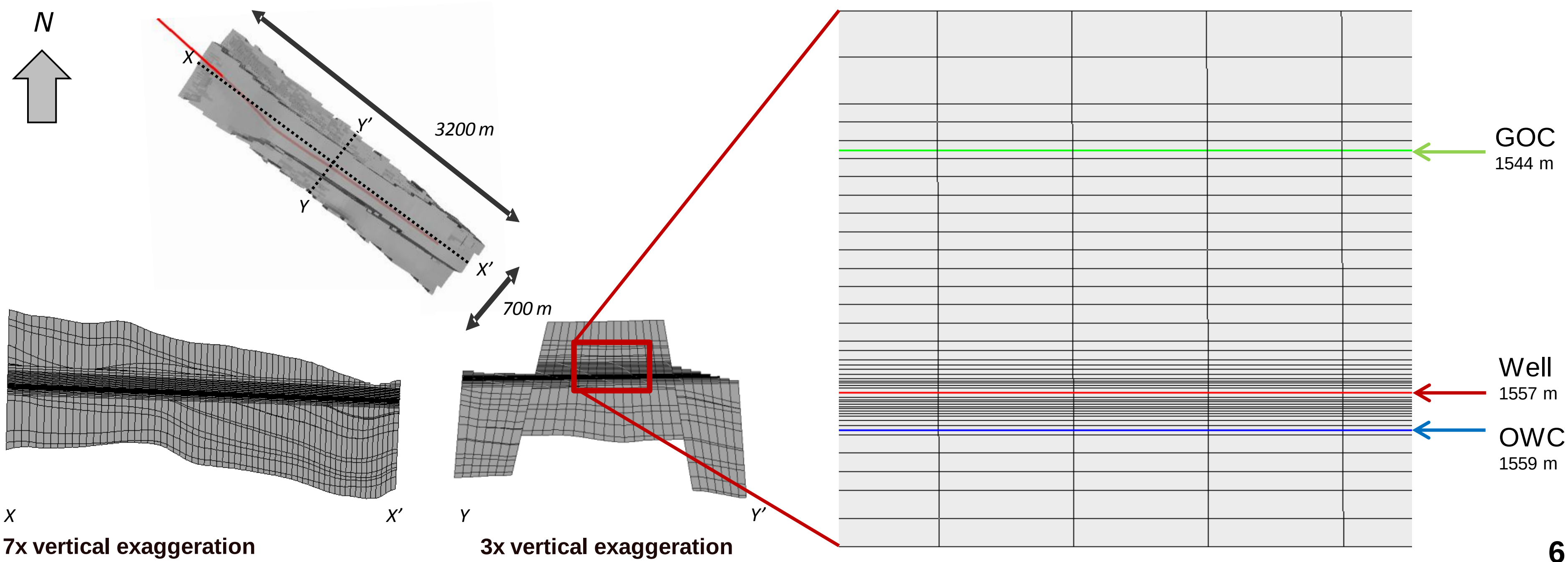




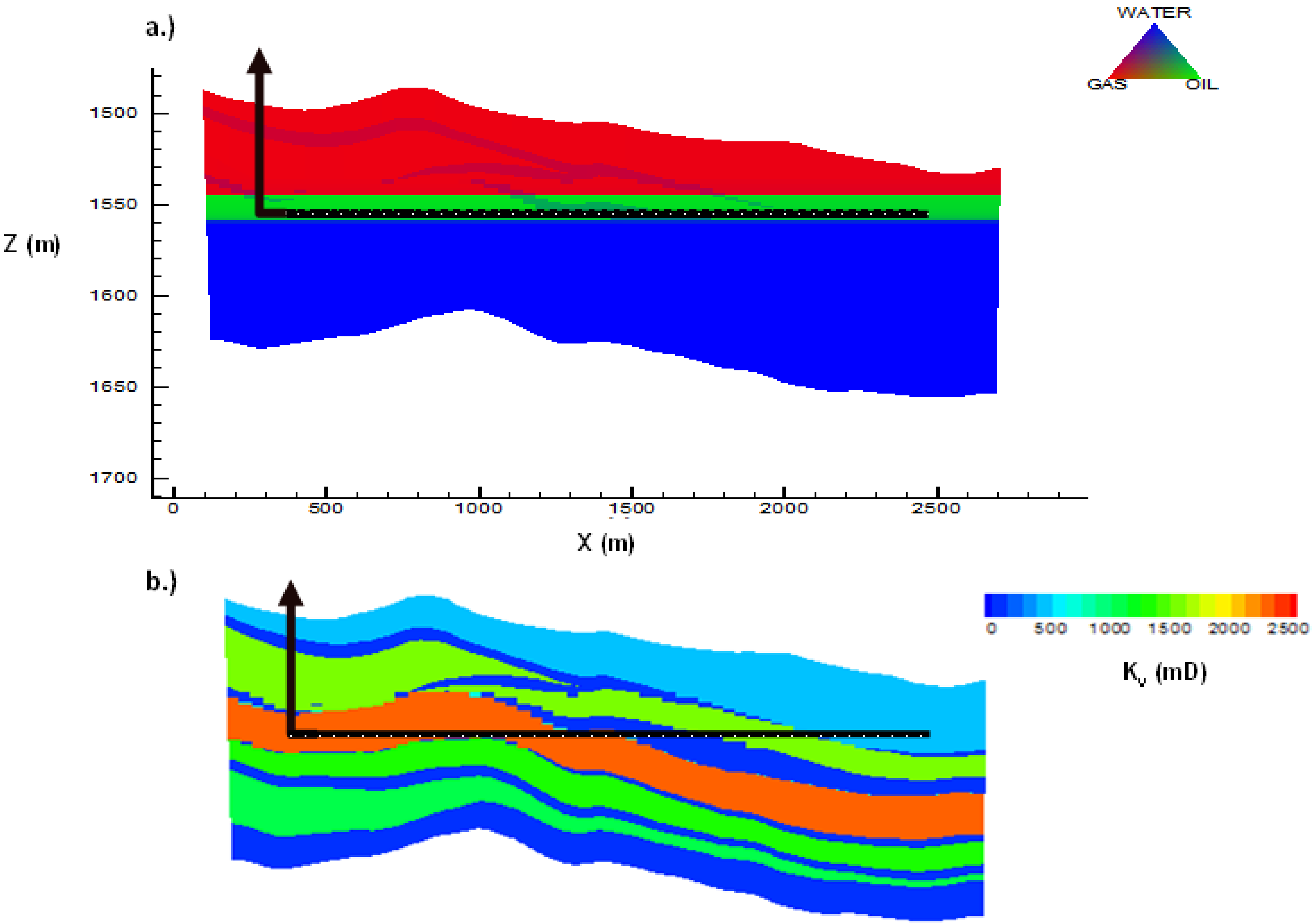
- Existing faults, flooding surfaces, and facies boundaries between fine-grained ('M') and coarse-grained ('C') sands taken directly from existing full-field geological model.

Model grid

- ❑ Active cells 80,000
- ❑ Areal grid resolution 50x25m
- ❑ Vertical grid resolution, hybrid grid approach of Vinje *et al.* (2011):
  - ➢ Stratigraphic grid in gas cap and aquifer
  - ➢ Horizontal and regular grid in oil column and 3m above and below GOC and OWC



Static and dynamic properties simplified from full-field model



13x vertical exaggeration

Dilib *et al*. (2012)

Modelling of 3-dimensional clinoforms in Troll Field

❑ Inputs to clinoform algorithm:

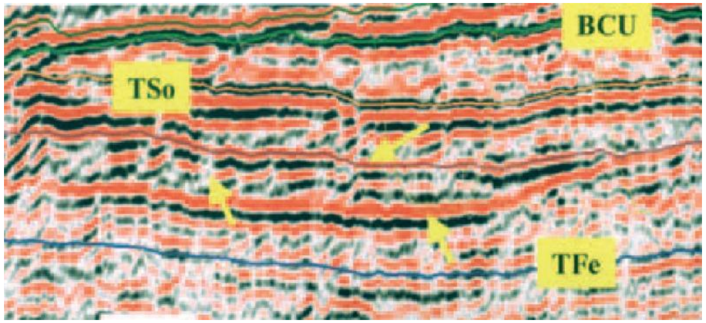
1. Stratigraphic surfaces bounding the rock volume within which clinoforms are generated:
   Existing stratigraphic framework

2. Cross-section geometry:
   Clinoform dip angle 1.5-4° (Dreyer *et al.* 2005)

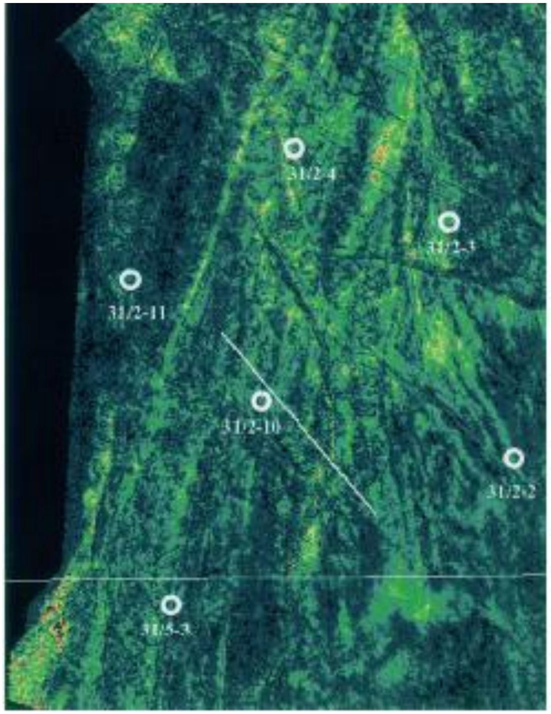
3. Plan view geometry:
   Linear (observed seismic data in Dreyer *et al.* 2005)

4. Progradation direction of the shoreline:
   W→NW (Dreyer *et al.* 2005)

3x vertical exaggeration



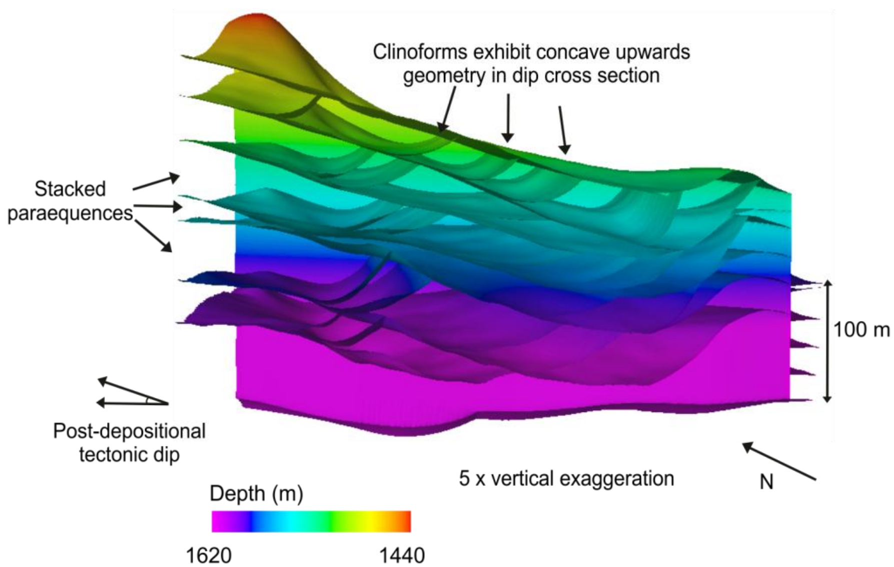
1 km

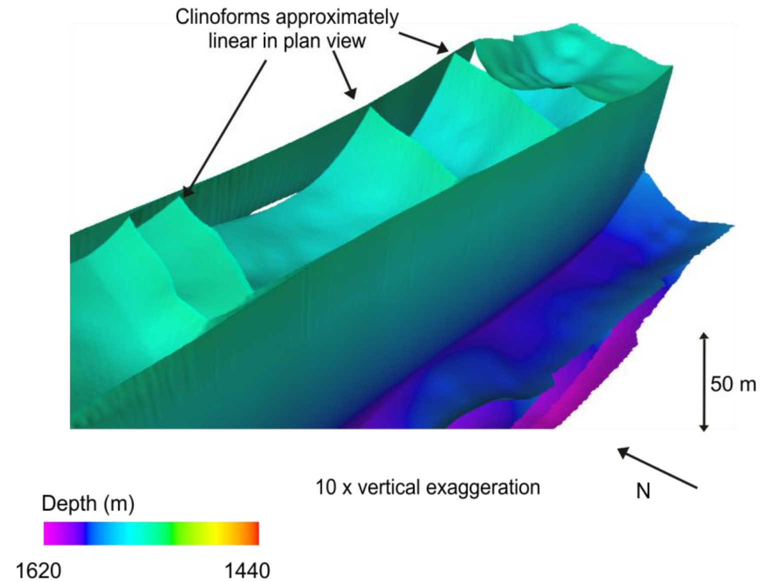


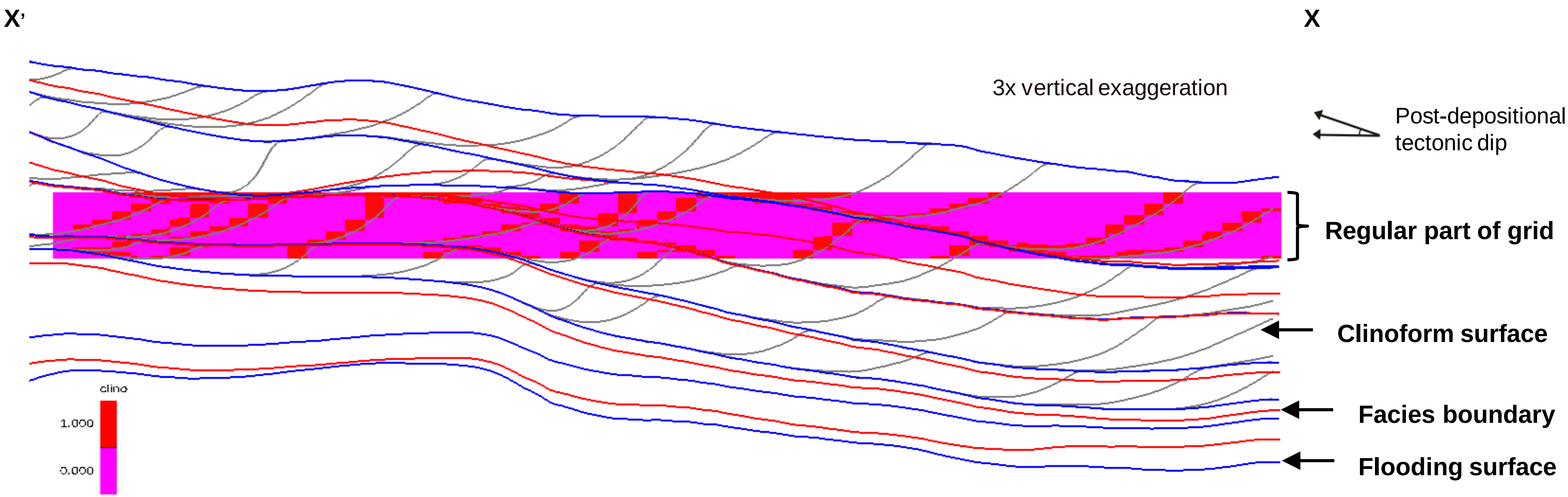
Dreyer *et al*. (2005)

Calcite cemented clinoforms and flooding surfaces

Graham *et al.*, In Review







Dilib *et al*. (2012)

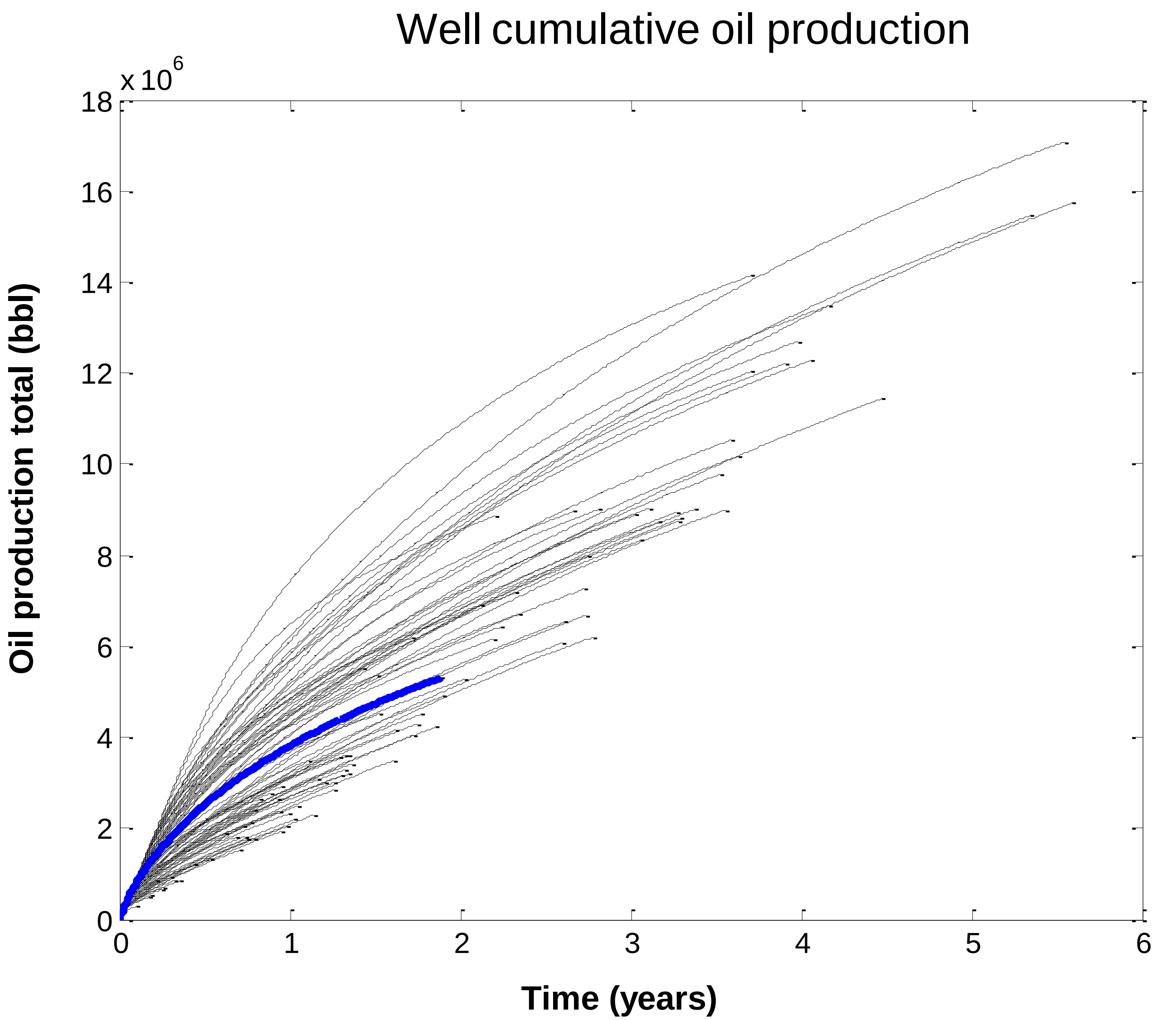
Reservoir uncertainty

	A	B	C	D	E	F	G	H
Factor	Fluid contacts	Thickness of oil column [m]	Relative perms [-]	Contrast M-C sand perm [-]	Cemented flooding surfaces (%)	Cemented clinoform surfaces (%)	M-sand Kv/Kh ratio [-]	C-sand Kv/Kh ratio [-]
Level 1	No capillary pressure	10	Pessimistic case	0.5x M-sand 2x C-sand	60	60	0.01	1
Level 2	Capillary pressure	15	Base case	1x M-sand 1xC-sand	0	0	0.1	0.5
Level 3	-	20	Optimistic case	4x M-sand 0.25x C-sand	90	90	-	-

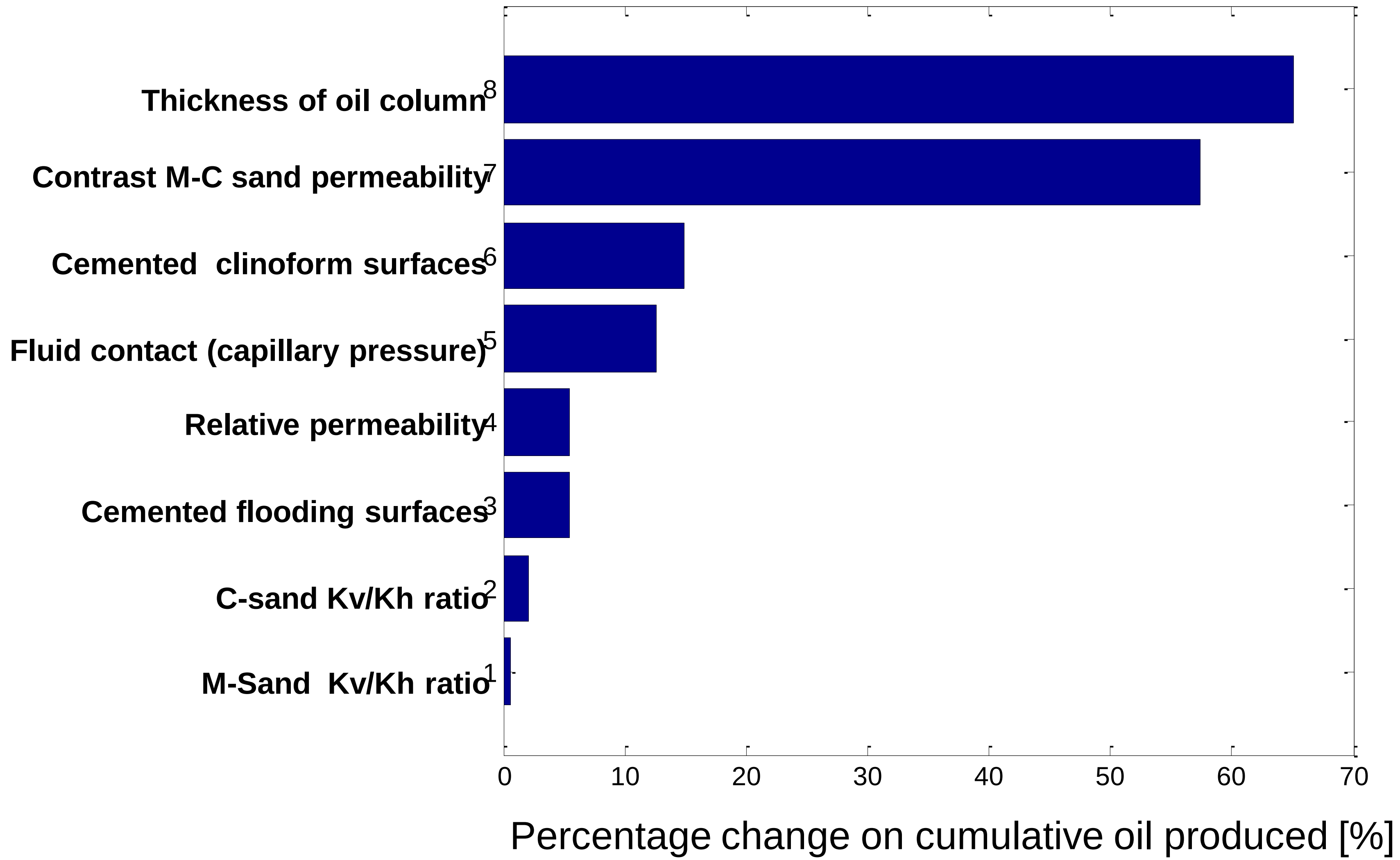
Base case: Troll full field simulation model

92 reservoir model realisations

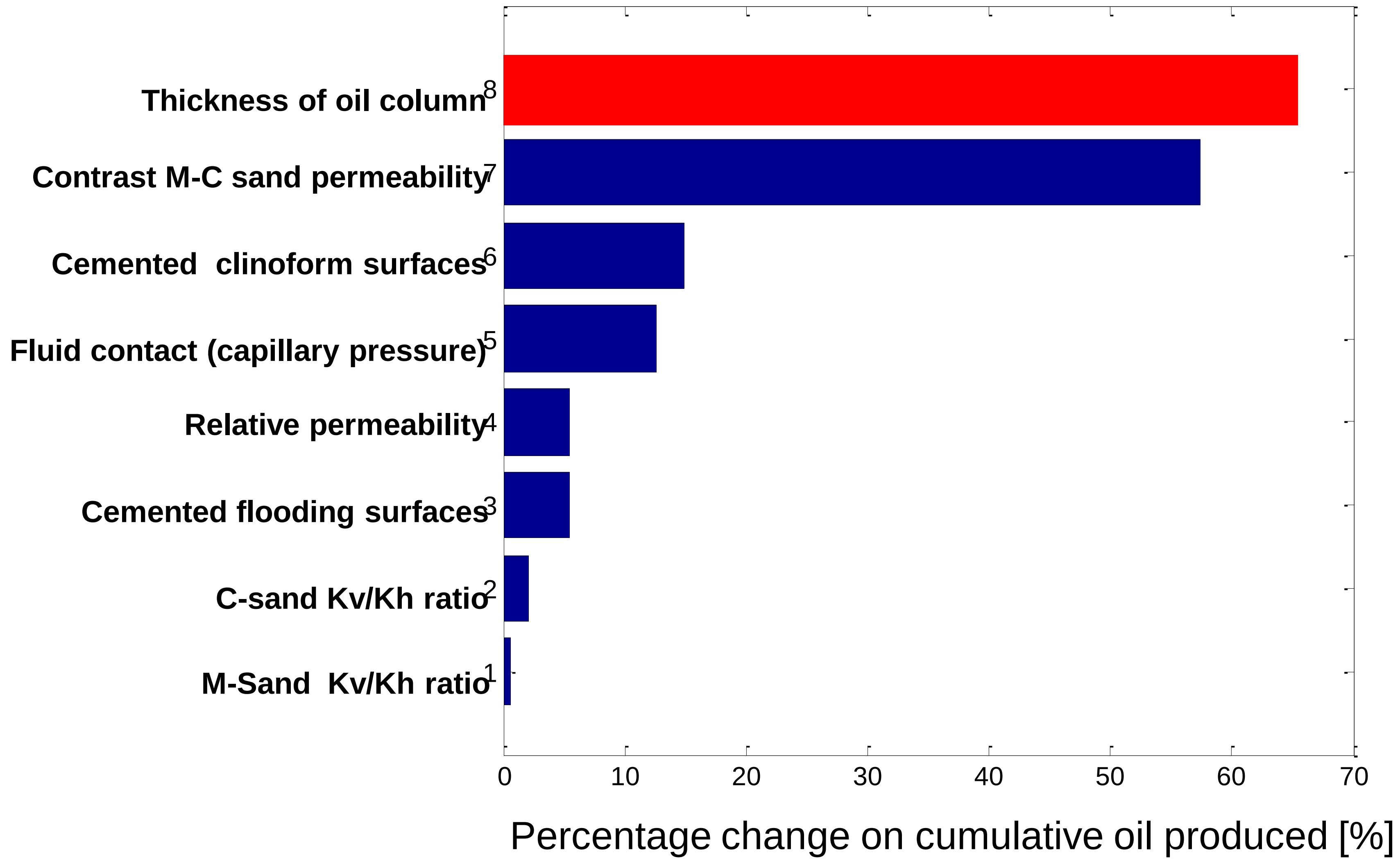
Effect of reservoir uncertainty on production



Ranking order of reservoir heterogeneity



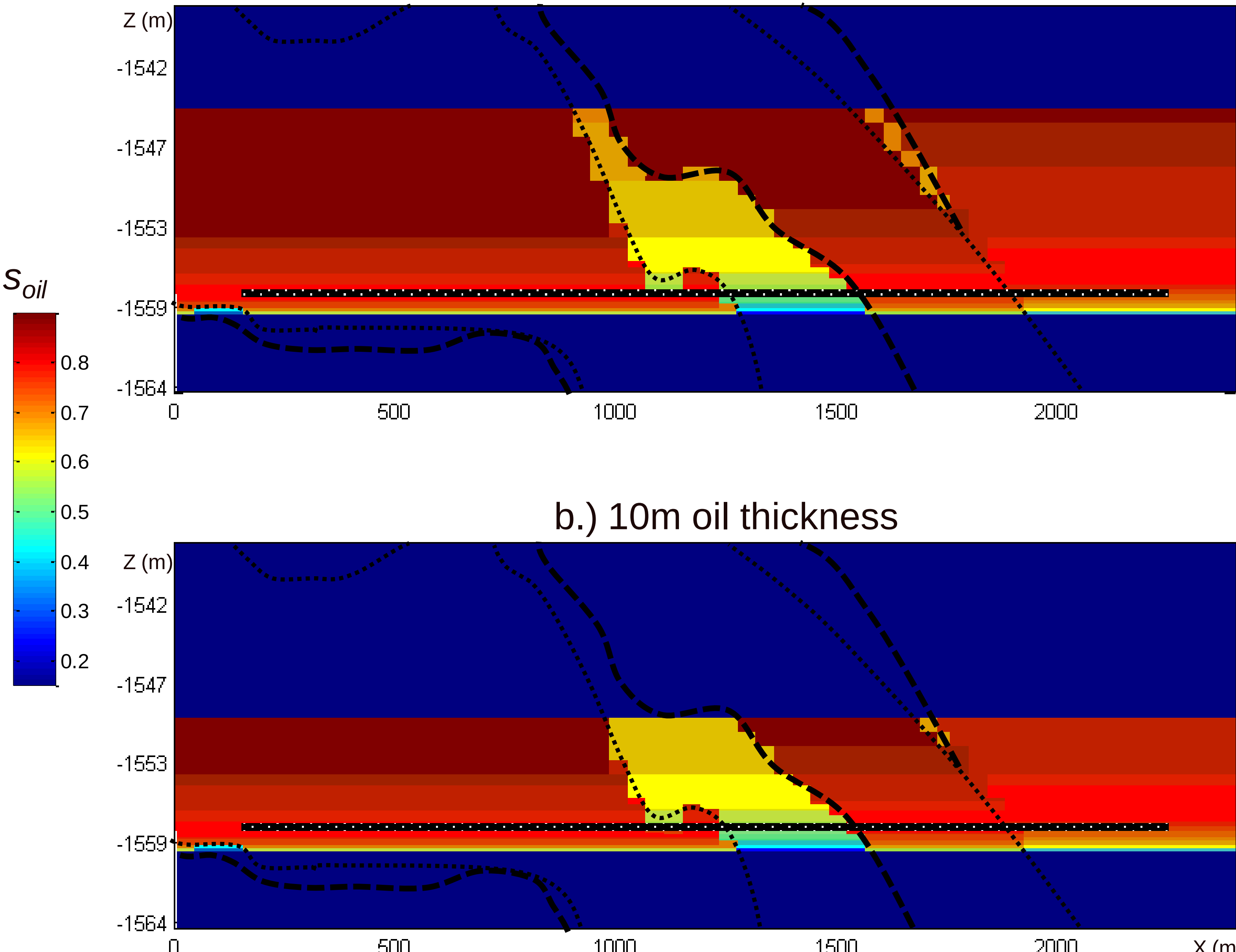
Ranking order of reservoir heterogeneity



TIME 0 days

Well production data

a.) 15m oil thickness (base case)



a.) **Gas-oil ratio** **0** **Sm3/Sm3**

Oil rate **0** **(Sm3/day)**

Watercut **0** **(-)**

b.) **Gas-oil ratio** **0** **(Sm3/Sm3)**

Oil rate **0** **(Sm3/day)**

Watercut **0** **(-)**

Flooding surfaces

Facies boundary surfaces

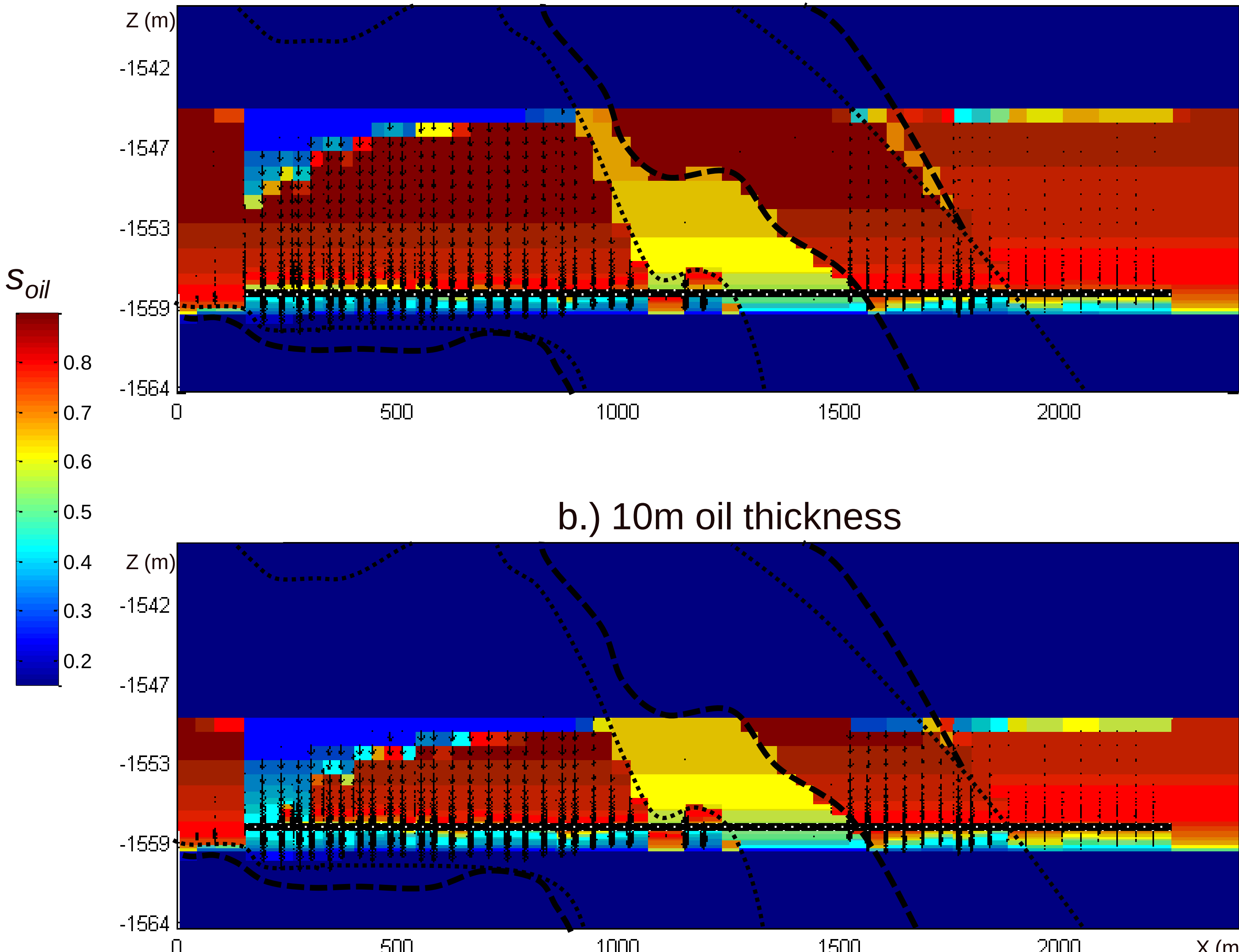
100x vertical exaggeration

Post-depositional tectonic dip

TIME 10 days

Well production data

a.) 15m oil thickness (base case)



a.)

Gas-oil ratio
64
(Sm3/Sm3)

Oil rate
3895
(Sm3/day)

Watercut
0.25
(-)

b.)

Gas-oil ratio
75
(Sm3/Sm3)

Oil rate
3297
(Sm3/day)

Watercut
0.25
(-)

100x vertical exaggeration

Flooding surfaces (dotted line)
Facies boundary surfaces (dashed line)

Post-depositional tectonic dip

TIME 400 days

Well production data

a.) 15m oil thickness (base case)

Gas-oil ratio
277
(Sm3/Sm3)

Oil rate
902
(Sm3/day)

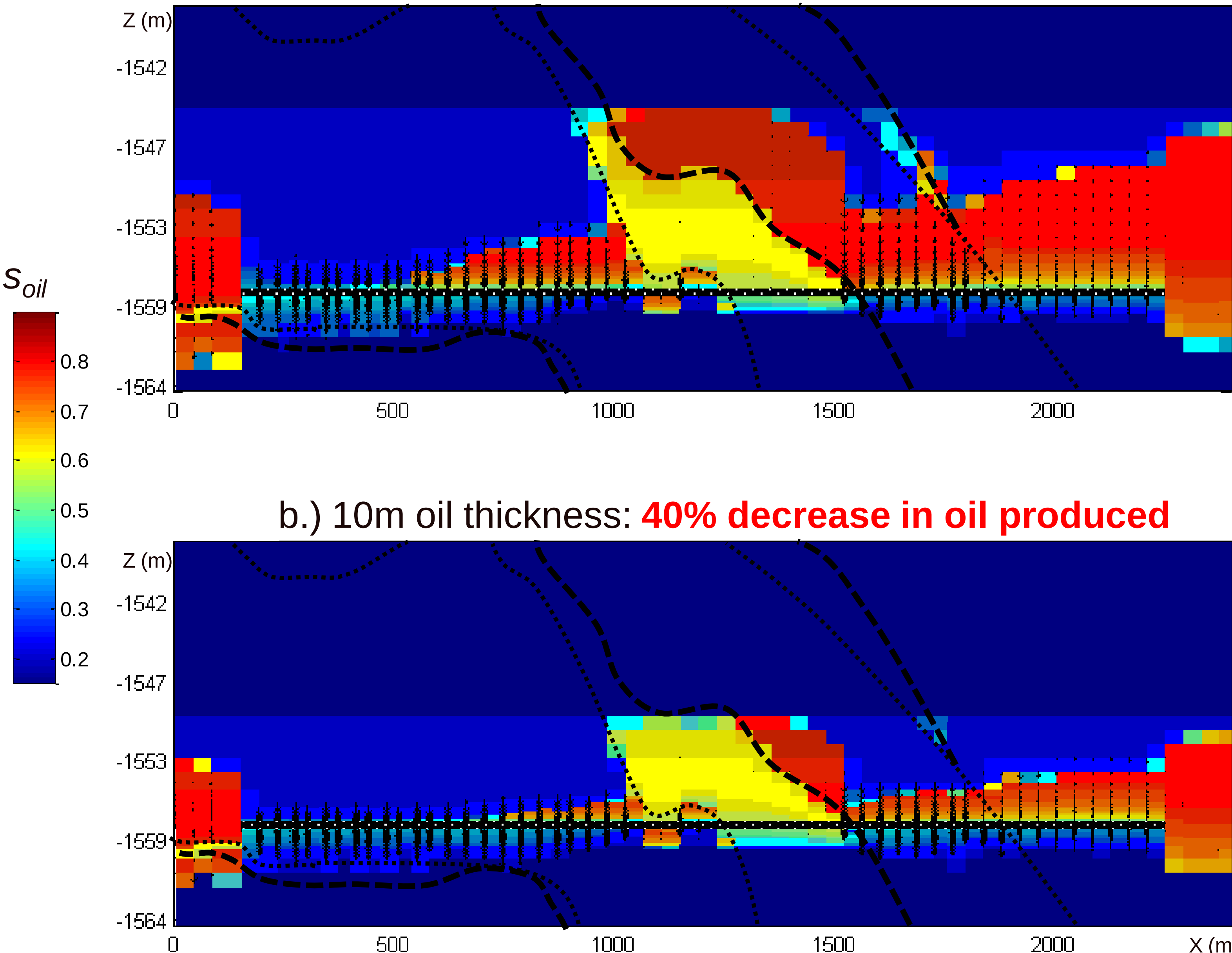
Watercut
0.64
(-)

b.) 10m oil thickness: **40% decrease in oil produced**

Gas-oil ratio
507
(Sm3/Sm3)

Oil rate
497
(Sm3/day)

Watercut
0.70
(-)

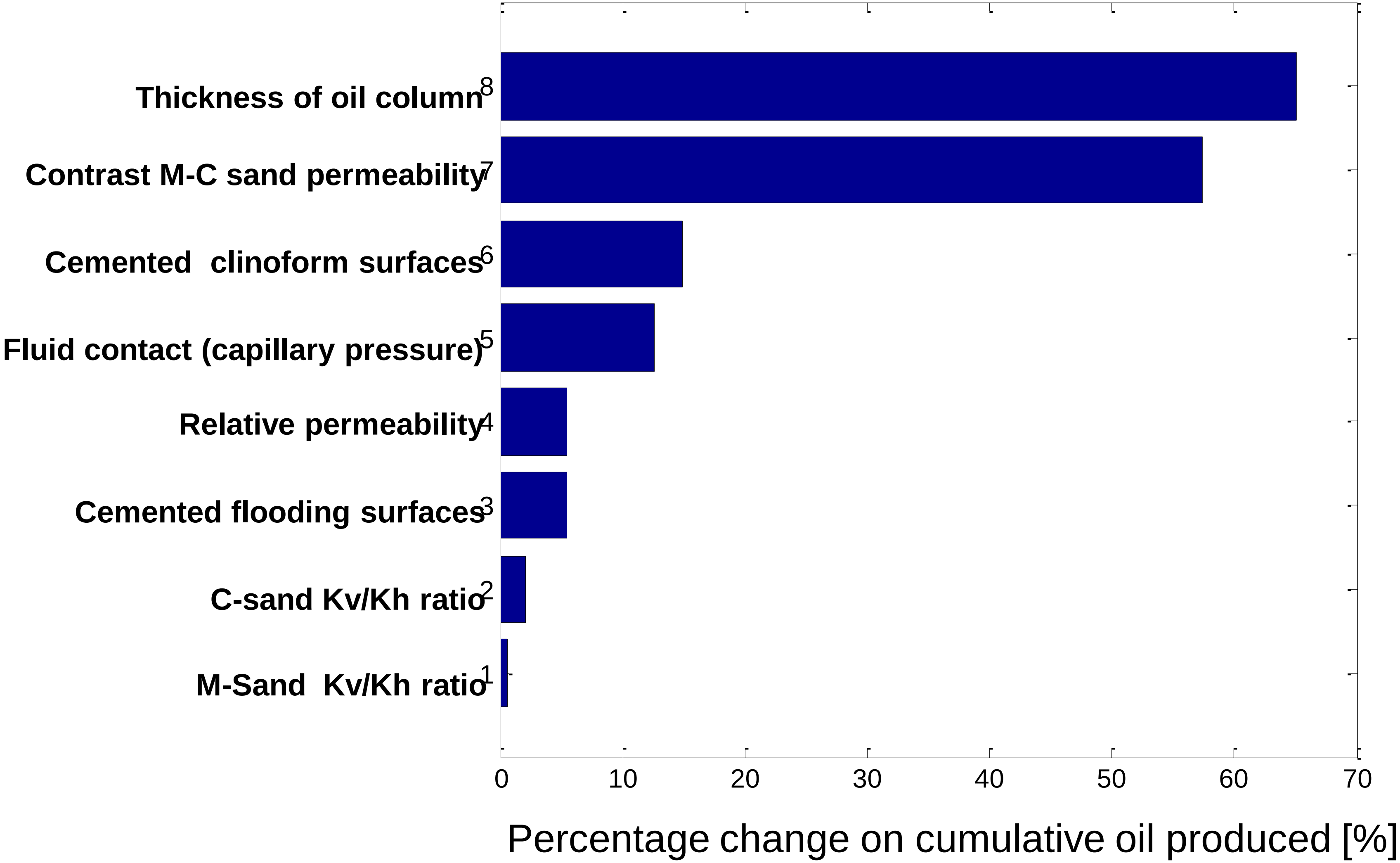


··················	**Flooding surfaces**
– – – – – – –	**Facies boundary surfaces**

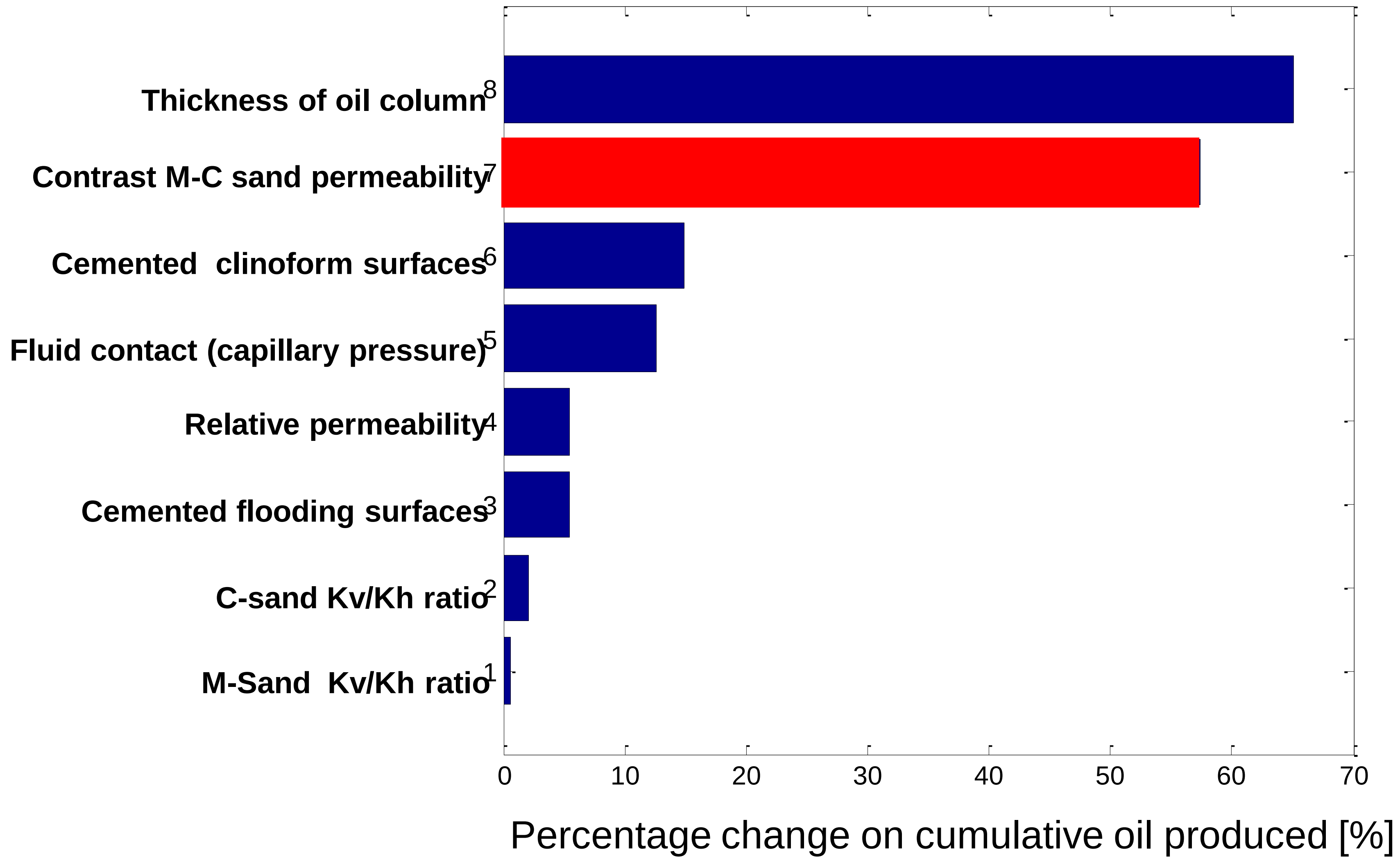
100x vertical exaggeration

Post-depositional tectonic dip

Ranking order of reservoir heterogeneity

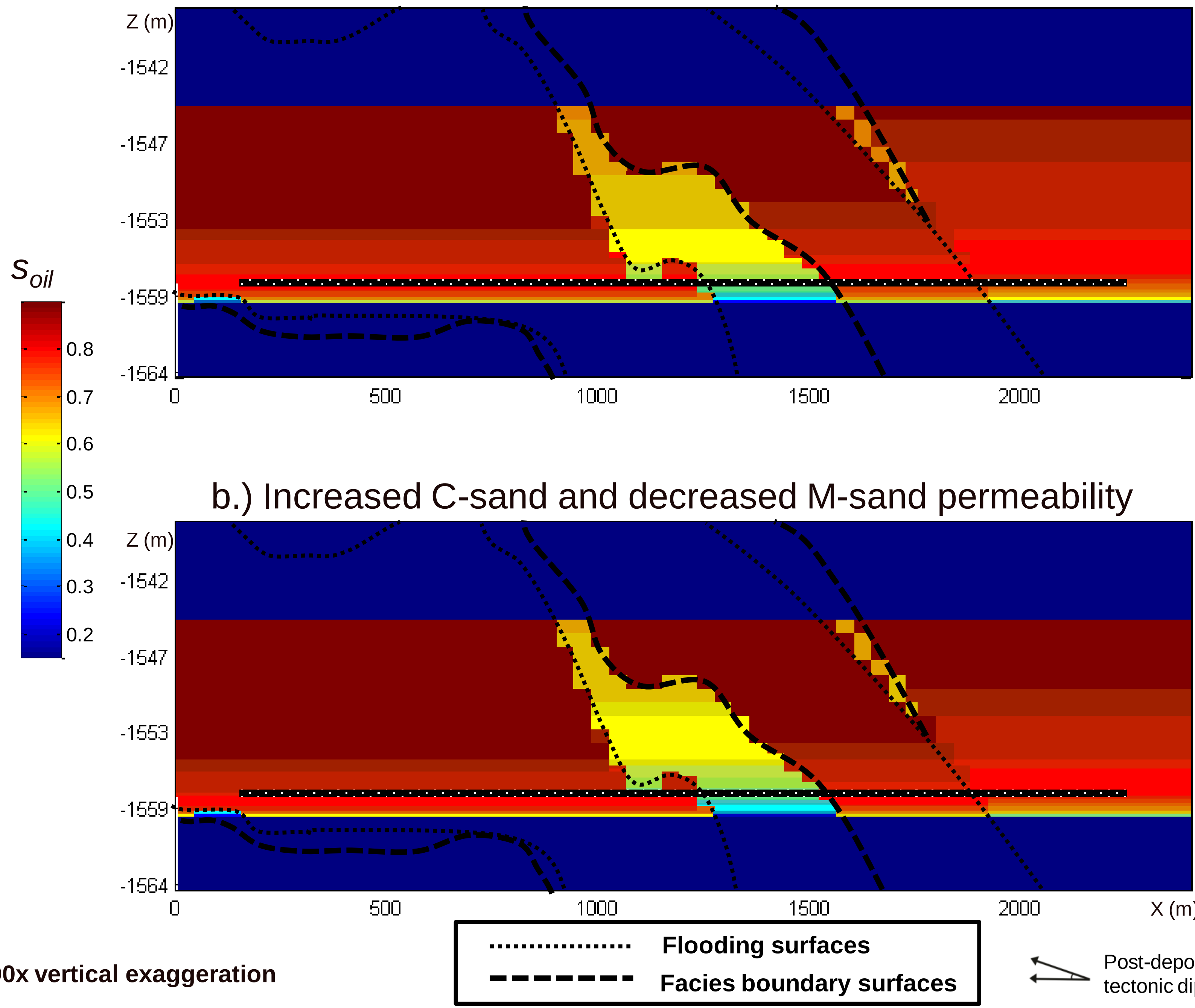


Ranking order of reservoir heterogeneity



TIME 0 days

Well production data



Gas-oil ratio
0
Sm3/Sm3

Oil rate
0
(Sm3/day)

Watercut
0
(-)

Gas-oil ratio
0
(Sm3/Sm3)

Oil rate
0
(Sm3/day)

Watercut
0
(-)

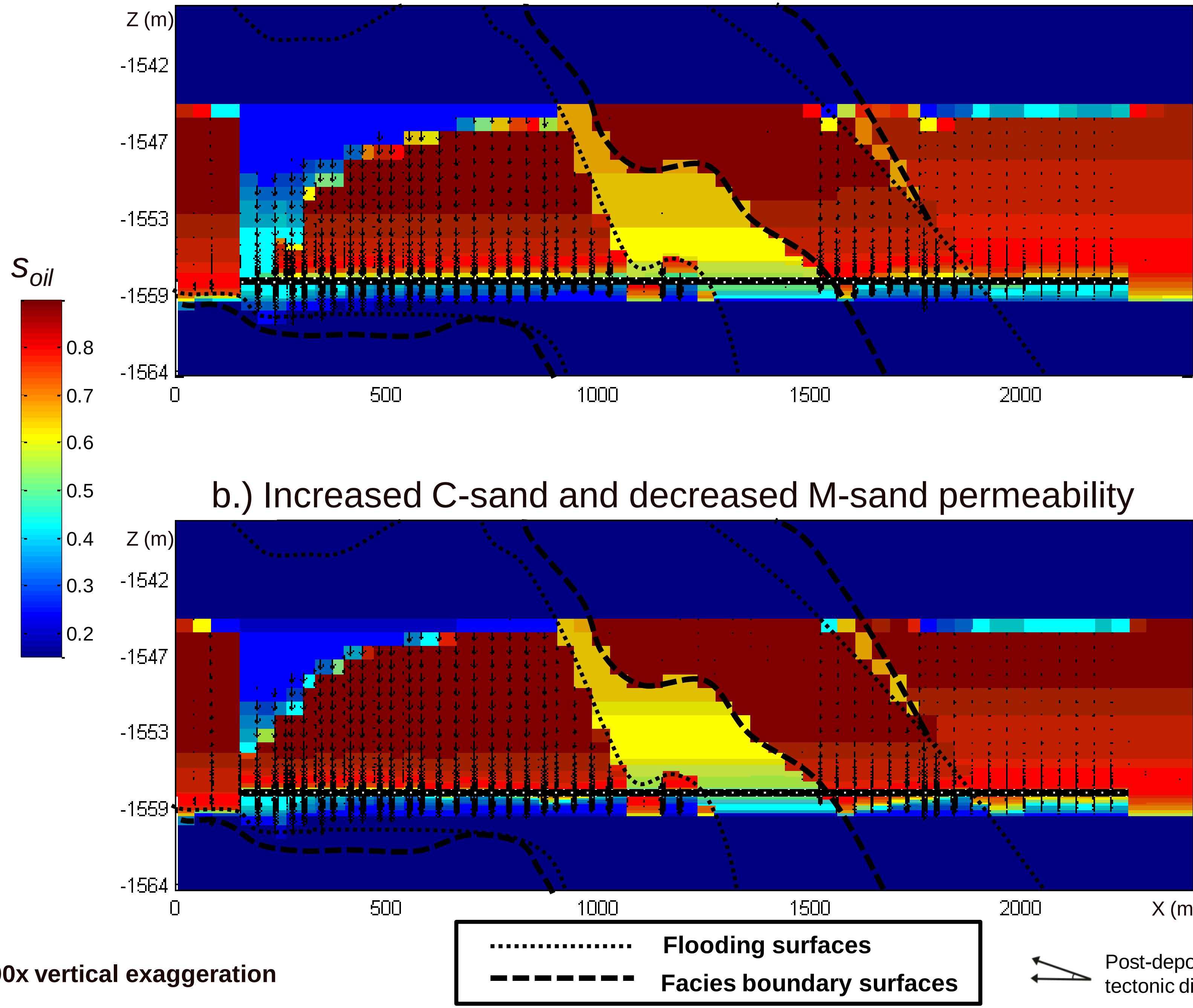
100x vertical exaggeration

Post-depositional tectonic dip

TIME 20 days

Well production data

a.) Base case model



a.)
Gas-oil ratio
69
Sm3/Sm3

Oil rate
3643
(Sm3/day)

Watercut
0.43
(-)

b.)
Gas-oil ratio
64
(Sm3/Sm3)

Oil rate
3911
(Sm3/day)

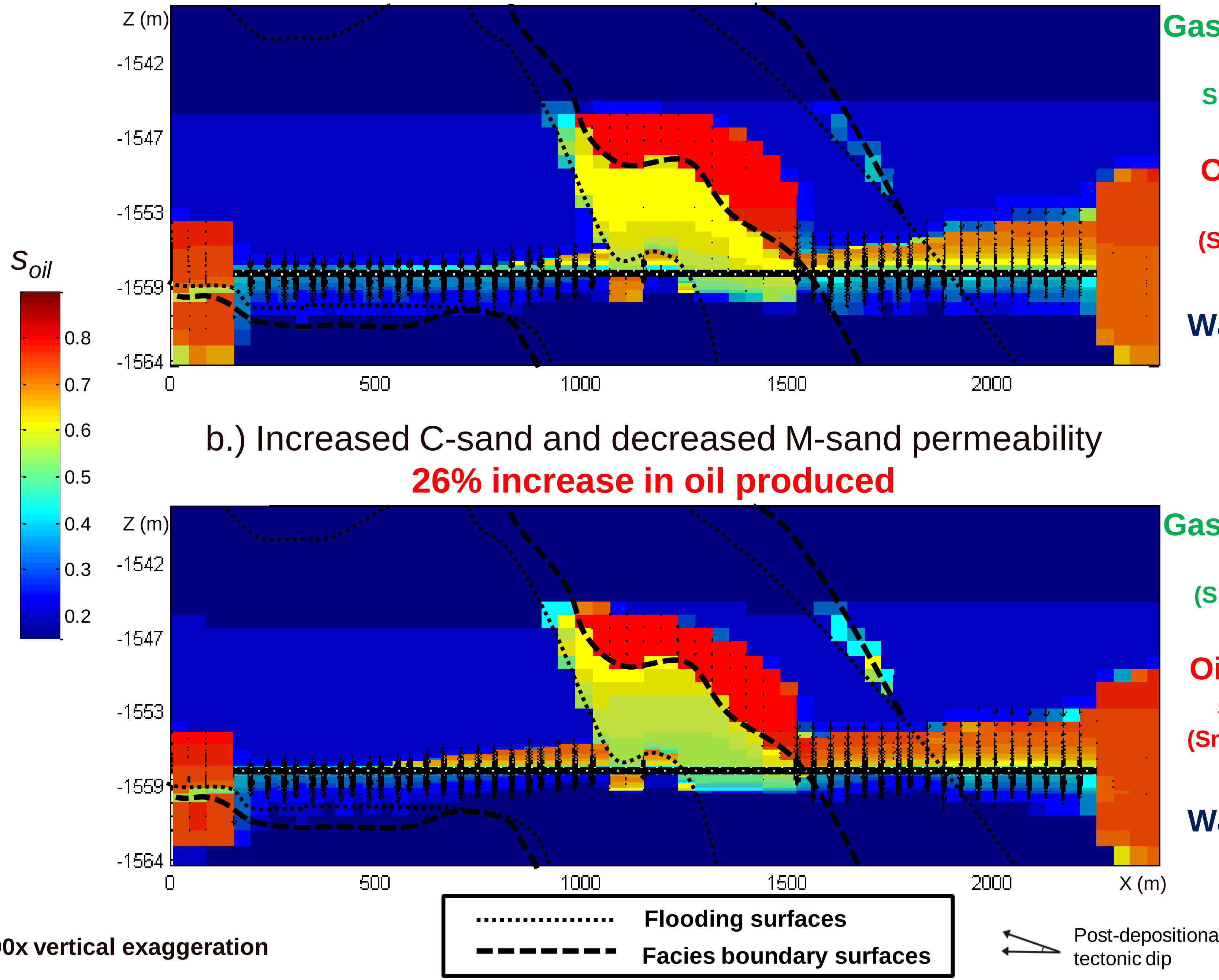
Watercut
0.35
(-)

100x vertical exaggeration

Post-depositional tectonic dip

TIME 1000 days

Well production data



a.) Base case model

Gas-oil ratio 584 Sm3/Sm3

Oil rate 428 (Sm3/day)

Watercut 0.63 (-)

b.) Increased C-sand and decreased M-sand permeability

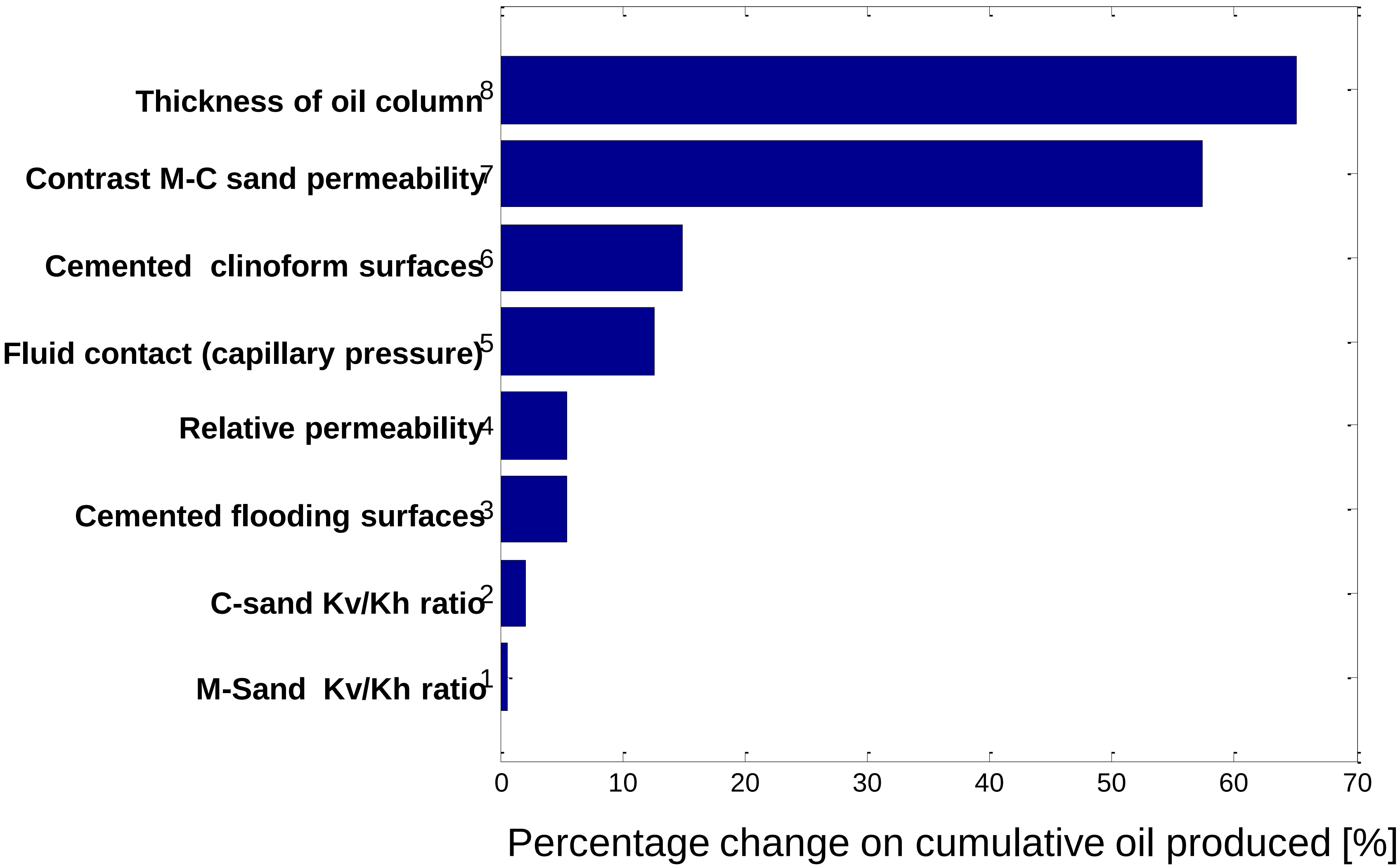
Gas-oil ratio 425 (Sm3/Sm3)

Oil rate 588 (Sm3/day)

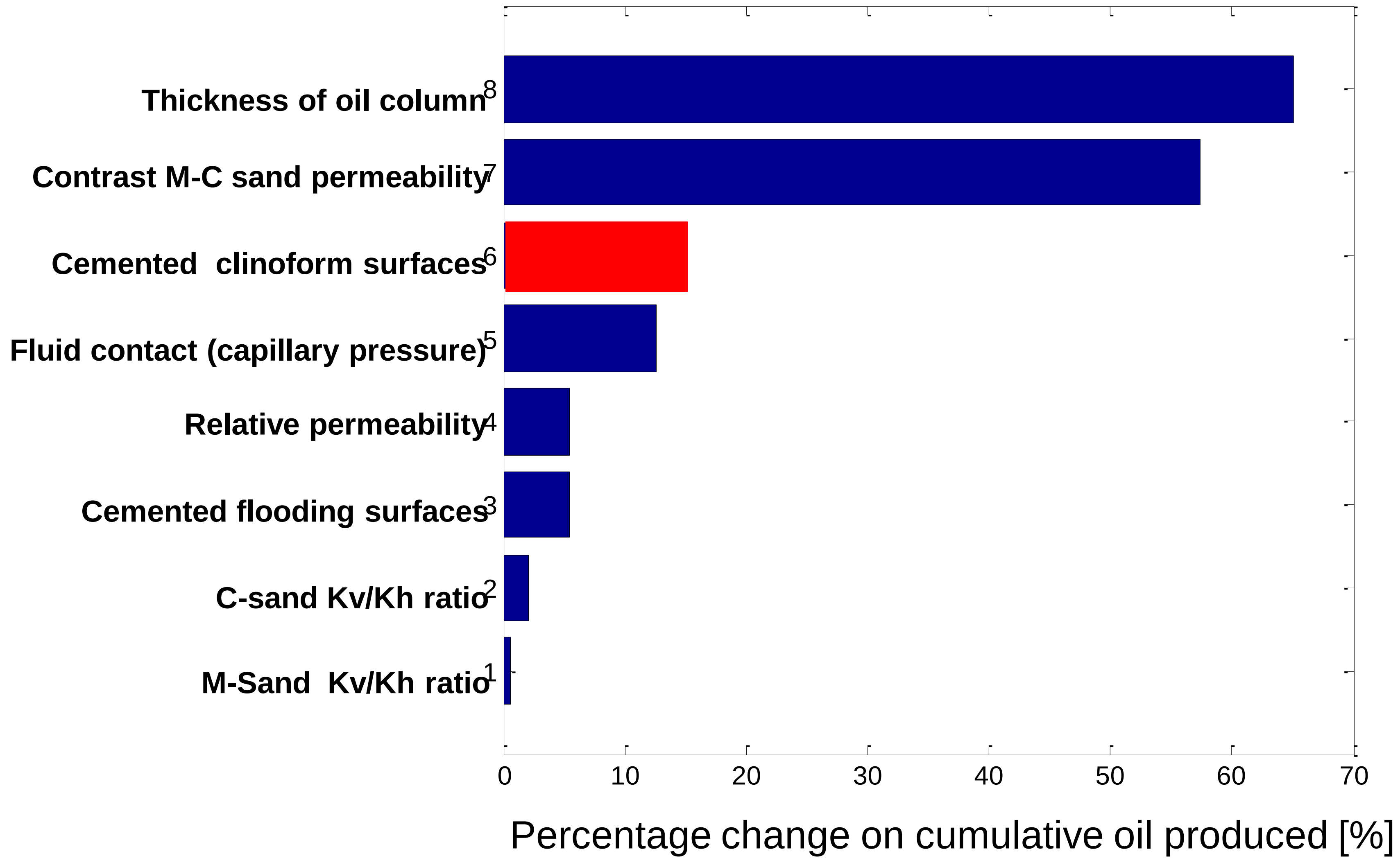
Watercut 0.53 (-)

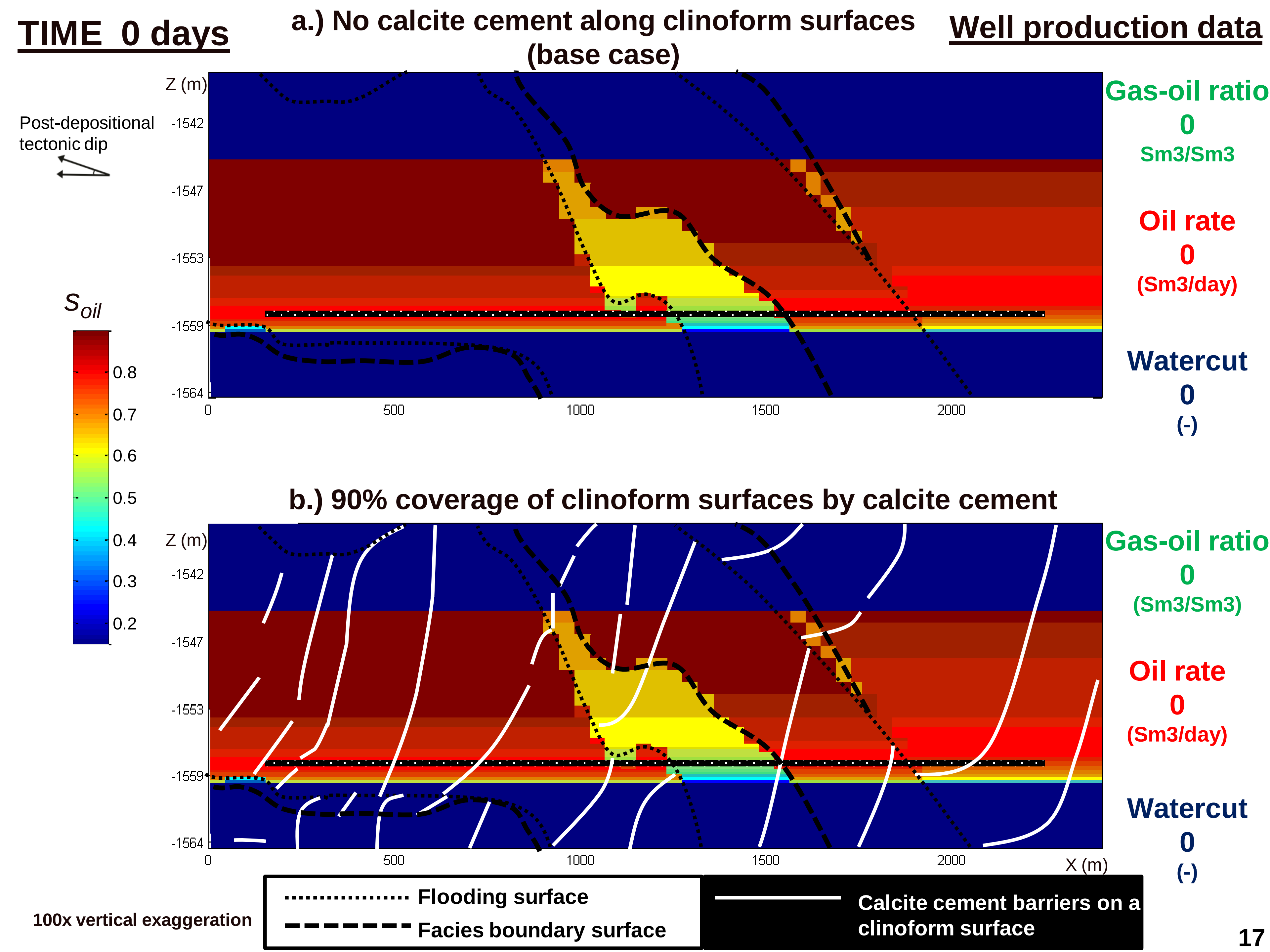
100x vertical exaggeration

Ranking order of reservoir heterogeneity



Ranking order of reservoir heterogeneity

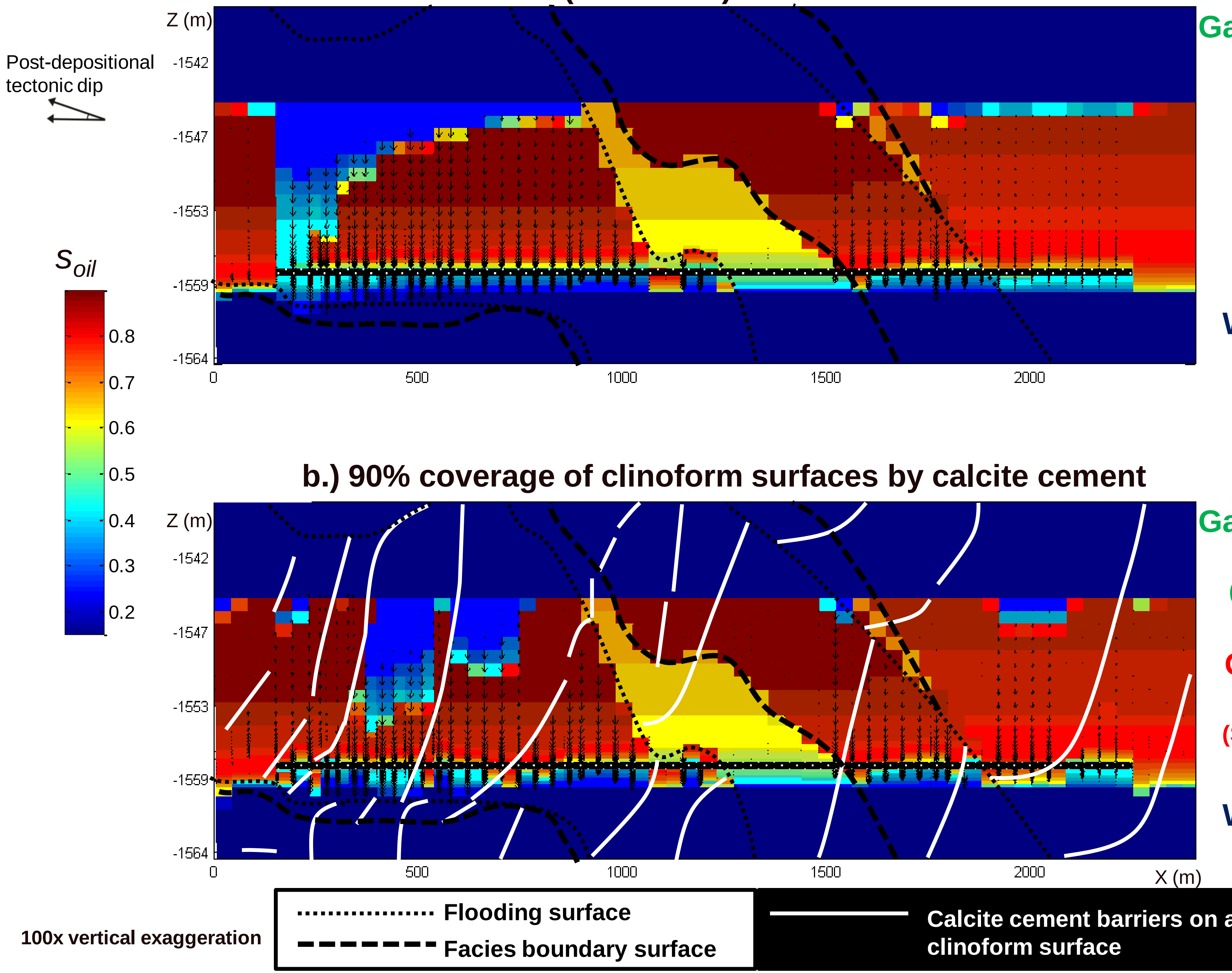



TIME 0 days
a.) No calcite cement along clinoform surfaces (base case)
Well production data
Post-depositional tectonic dip
Z (m)
-1542
-1547
-1553
-1559
-1564
0
500
1000
1500
2000
Gas-oil ratio
0
Sm3/Sm3
Oil rate
0
(Sm3/day)
Watercut
0
(-)
S_{oil}
0.8
0.7
0.6
0.5
0.4
0.3
0.2
b.) 90% coverage of clinoform surfaces by calcite cement
Z (m)
-1542
-1547
-1553
-1559
-1564
0
500
1000
1500
2000
X (m)
Gas-oil ratio
0
(Sm3/Sm3)
Oil rate
0
(Sm3/day)
Watercut
0
(-)
100x vertical exaggeration
Flooding surface
Facies boundary surface
Calcite cement barriers on a clinoform surface

TIME 20 days

a.) No calcite cement along clinoform surfaces (base case)

b.) 90% coverage of clinoform surfaces by calcite cement



Well production data

a.)

Gas-oil ratio
69
Sm3/Sm3

Oil rate
3643
(Sm3/day)

Watercut
0.43
(-)

b.)

Gas-oil ratio
64
(Sm3/Sm3)

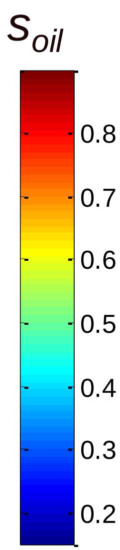
Oil rate
3923
(Sm3/day)

Watercut
0.20
(-)

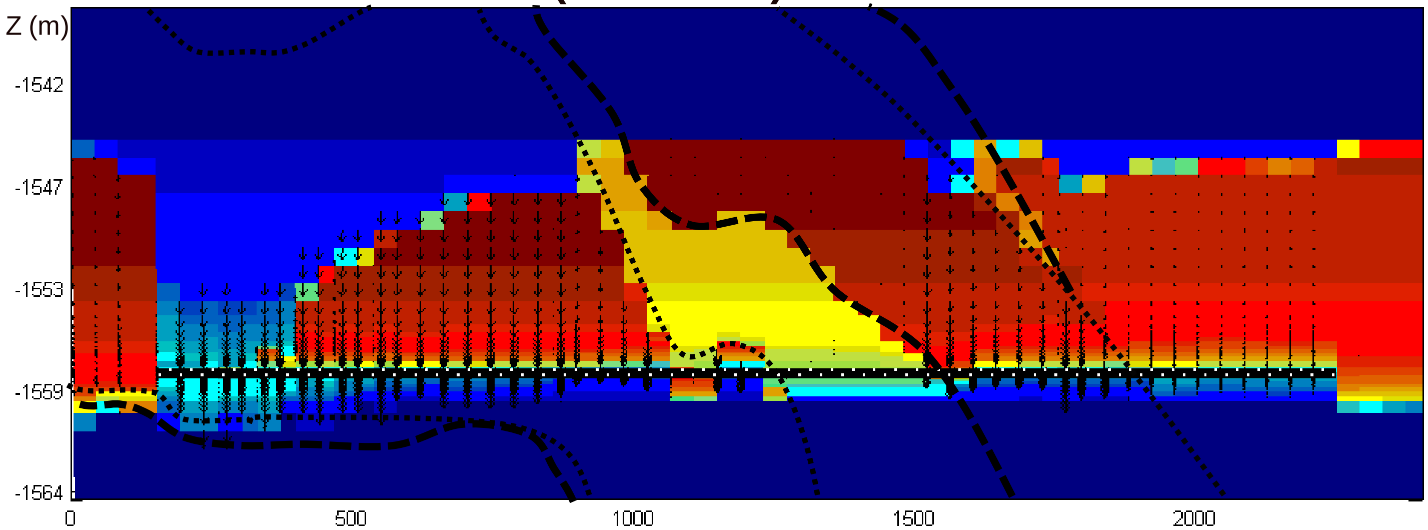
TIME 60 days

Well production data

Post-depositional tectonic dip



a.) No calcite cement along clinoform surfaces (base case)

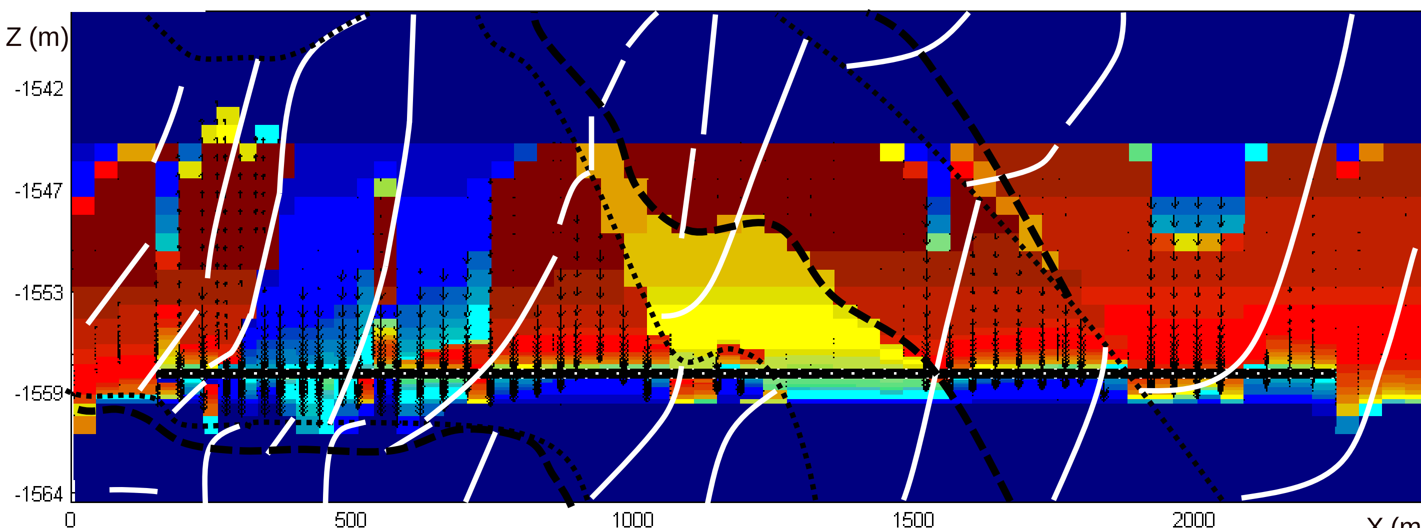


Gas-oil ratio
110
Sm3/Sm3

Oil rate
2269
(Sm3/day)

Watercut
0.57
(-)

b.) 90% coverage of clinoform surfaces by calcite cement



Gas-oil ratio
119
(Sm3/Sm3)

Oil rate
2102
(Sm3/day)

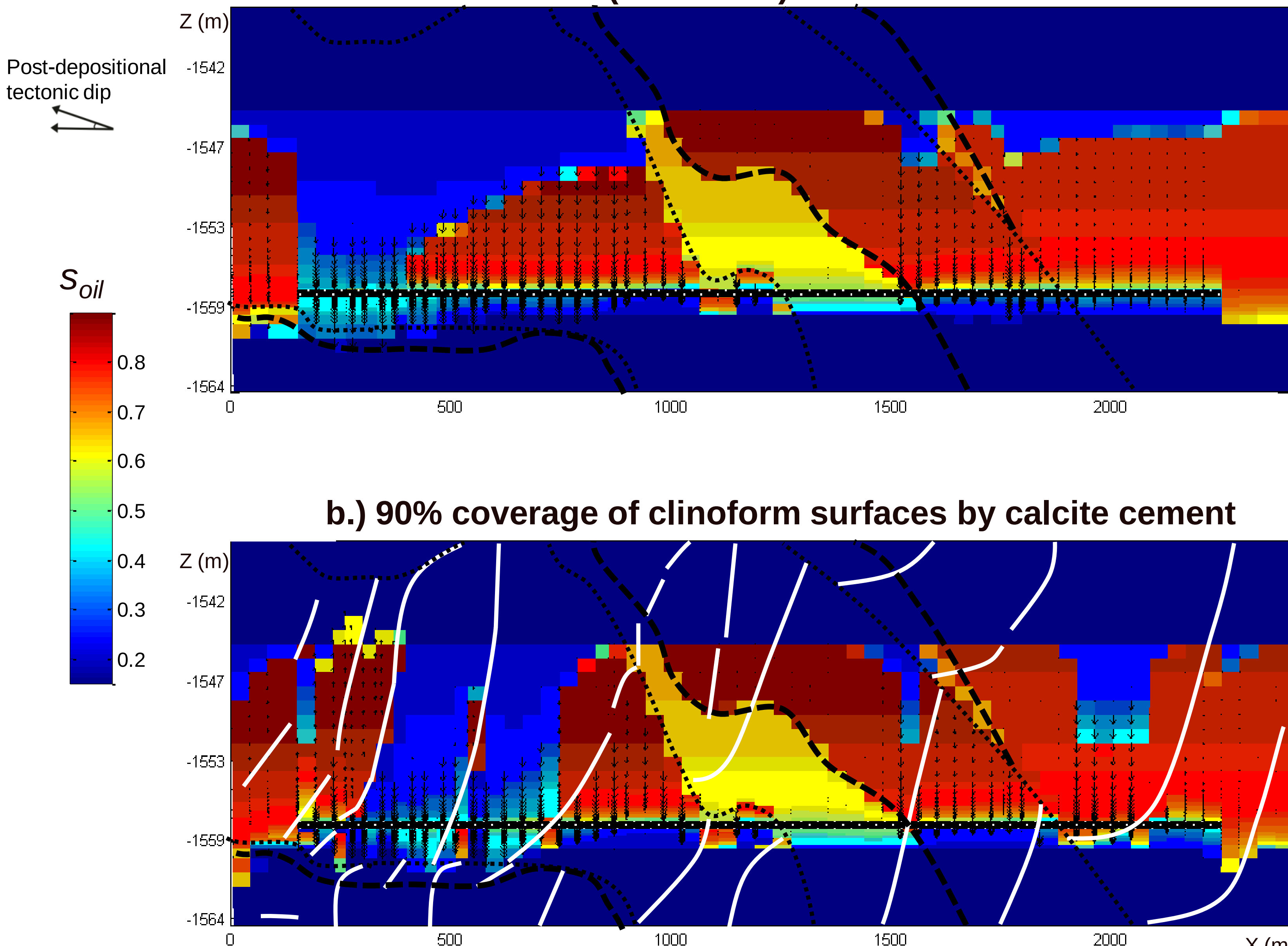
Watercut
0.38
(-)

100x vertical exaggeration

··········· **Flooding surface**	——— **Calcite cement barriers on a clinoform surface**
– – – – **Facies boundary surface**	

TIME 100 days

a.) No calcite cement along clinoform surfaces (base case)



Well production data

a.)

Gas-oil ratio 136 Sm3/Sm3

Oil rate 1834 (Sm3/day)

Watercut 0.60 (-)

b.)

Gas-oil ratio 161 (Sm3/Sm3)

Oil rate 1549 (Sm3/day)

Watercut 0.44 (-)

100x vertical exaggeration

Flooding surface (dotted line)

Facies boundary surface (dashed line)

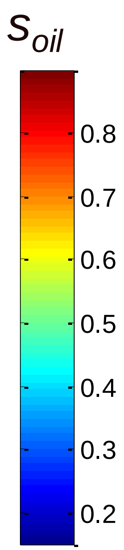
Calcite cement barriers on a clinoform surface (white line)

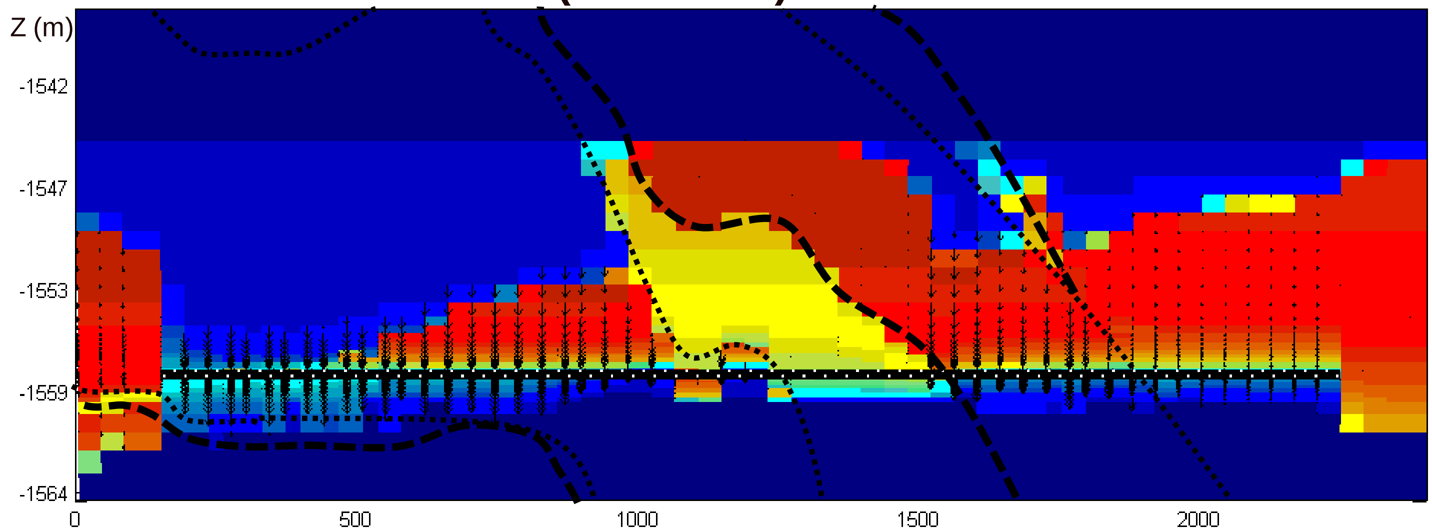
TIME 300 days

a.) No calcite cement along clinoform surfaces (base case)

Well production data

Post-depositional tectonic dip



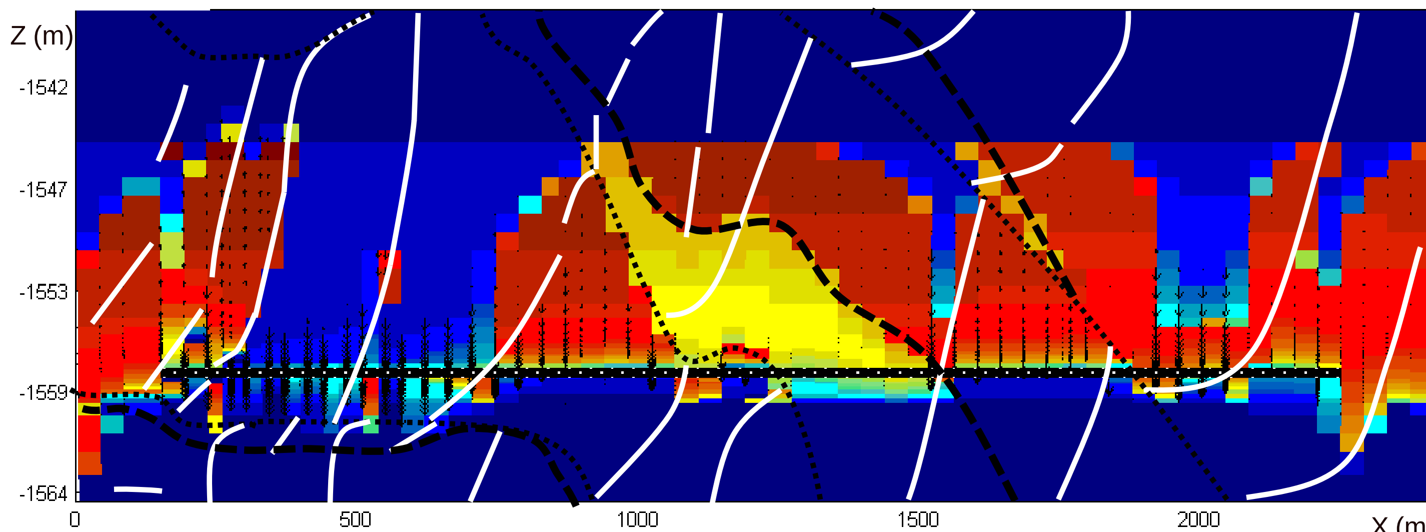


Gas-oil ratio
234
Sm3/Sm3

Oil rate
1070
(Sm3/day)

Watercut
0.64
(-)

b.) 90% coverage of clinoform surfaces by calcite cement



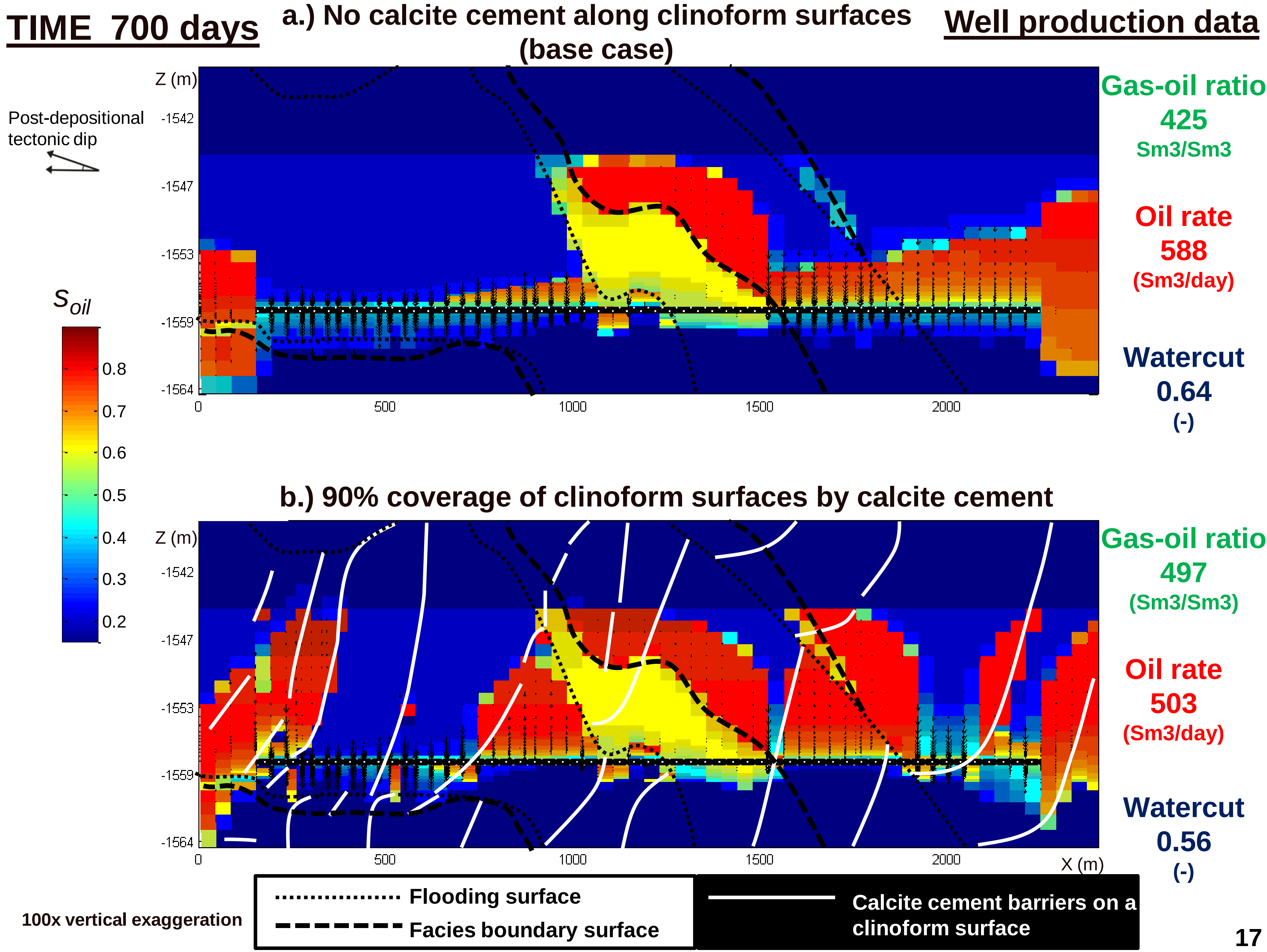
Gas-oil ratio
299
(Sm3/Sm3)

Oil rate
836
(Sm3/day)

Watercut
0.53
(-)

100x vertical exaggeration

Flooding surface (dotted line)
Facies boundary surface (dashed line)
Calcite cement barriers on a clinoform surface (white line)


TIME 700 days
a.) No calcite cement along clinoform surfaces (base case)
Well production data
Post-depositional tectonic dip
Z (m)
-1542
-1547
-1553
-1559
-1564
0
500
1000
1500
2000
Gas-oil ratio
425
Sm3/Sm3
Oil rate
588
(Sm3/day)
Watercut
0.64
(-)
S oil
0.8
0.7
0.6
0.5
0.4
0.3
0.2
b.) 90% coverage of clinoform surfaces by calcite cement
Gas-oil ratio
497
(Sm3/Sm3)
Oil rate
503
(Sm3/day)
Watercut
0.56
(-)
X (m)
100x vertical exaggeration
Flooding surface
Facies boundary surface
Calcite cement barriers on a clinoform surface

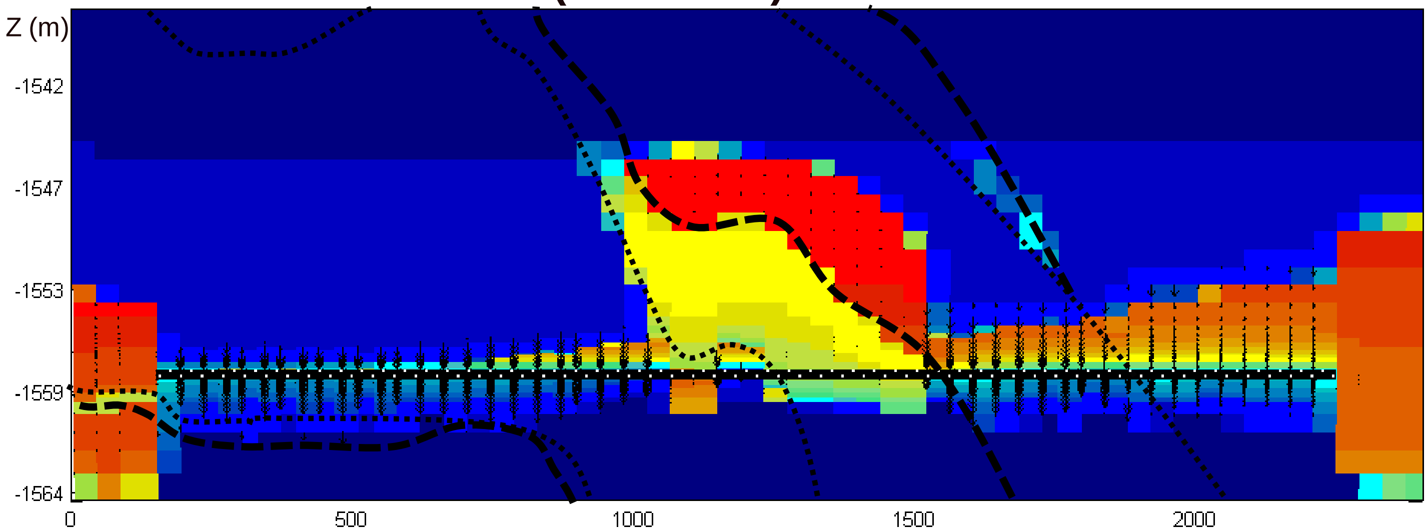
TIME 900 days

Well production data

Post-depositional tectonic dip

S_{oil}

a.) No calcite cement along clinoform surfaces (base case)



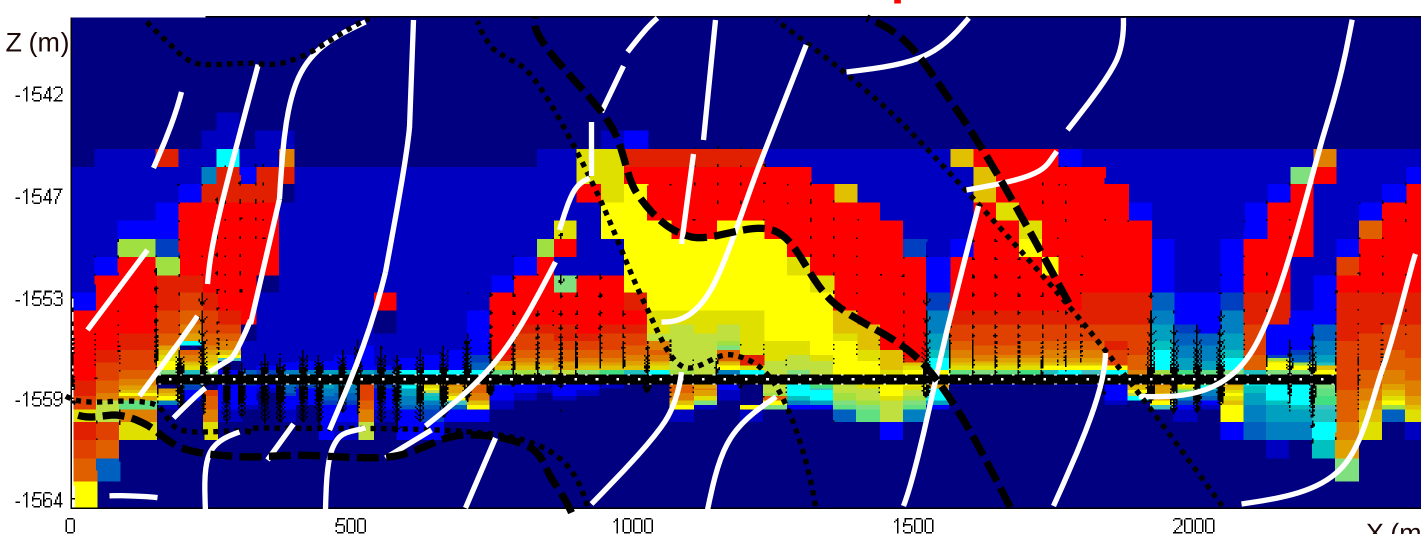
Gas-oil ratio 527 Sm3/Sm3

Oil rate 475 (Sm3/day)

Watercut 0.64 (-)

b.) 90% coverage of clinoform surfaces by calcite cement

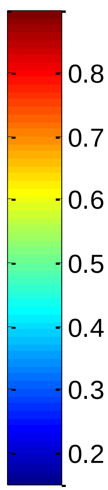
13% decrease in oil produced



Gas-oil ratio 550 (Sm3/Sm3)

Oil rate 454 (Sm3/day)

Watercut 0.56 (-)



100x vertical exaggeration

Flooding surface

Facies boundary surface

Calcite cement barriers on a clinoform surface

Conclusions

- Most significant uncertainty: thickness of the oil column and contrast between M-sand and C-sand permeability

- Calcite-cemented clinoform surfaces also have a significant impact on oil production

BUT

- Clinoforms not typically included in reservoir modelling and simulation workflows but they can have an impact on oil production and reservoir sweep

- Implications for history matching:
  - Wrong parameter(s) adjusted
  - Erroneous predictions of future reservoir behaviour