IORSim Geochem Module

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Why do we need geochemistry?

- We know fluid chemistry affects flow properties on core scale (~10 cm)
  1. Compaction and wettability in chalk
  2. Water diverging
  3. Low salinity effects

Scaling in producers
H2S and reservoir souring

- How to translate core scale knowledge/processes to field scale?
  - *Implementation* of IOR processes
  - *Interpretation* of field data

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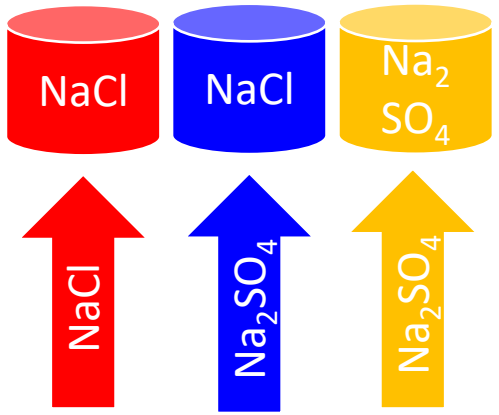
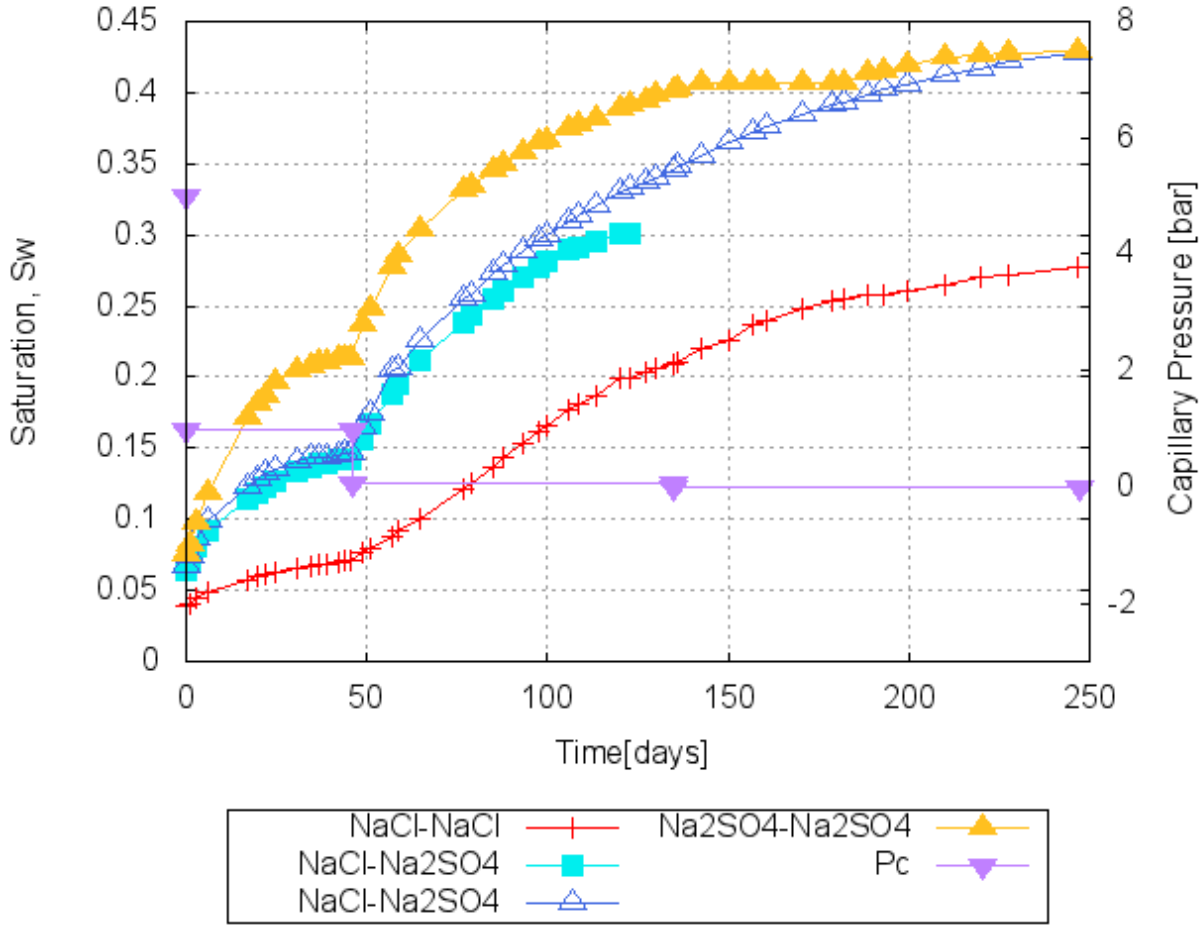
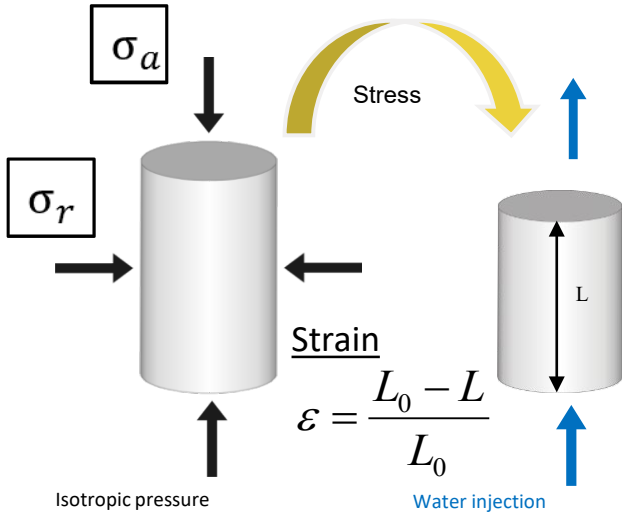
Effect of sulphate on oil production

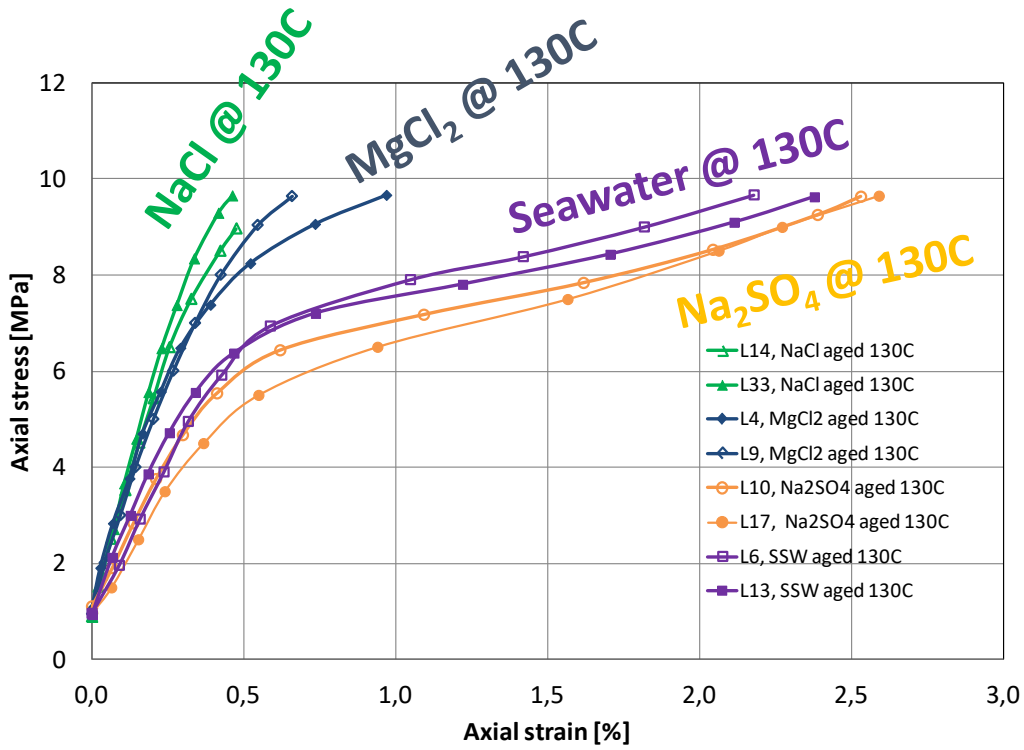




R. Ahsan, M. V. Madland , F. Bratteli, A. Hiorth "A STUDY OF SULPHATE IONS - EFFECTS ON AGEING AND IMBIBITION CAPILLARY PRESSURE CURVE" – SCA, **34** (2012)

SO4 affects Yield – hydrostatic test

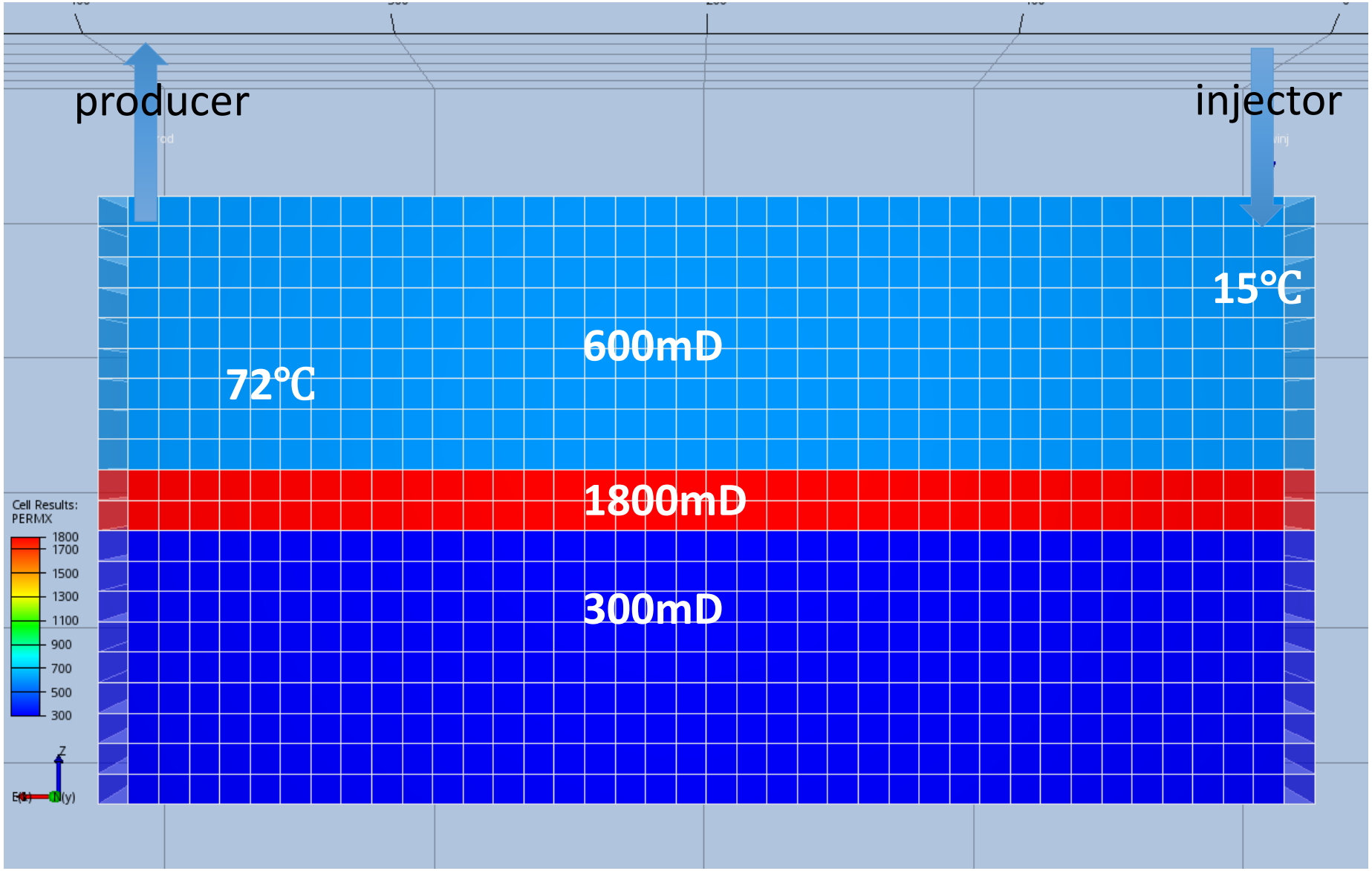




Liege chalk, Porosity = 40.3 – 41.8%

Megawati, M., Hiorth, A., Madland, M.V., (2012), The impact of surface charge on the mechanical behaviour of high-porosity chalk, Rock Mechanics and Rock Engineering-Springer

Synthethic model (IORCoreSim results)



Two cases:
1. 0.1wt% CO_2 in oil
2. 10^{-4}wt% CO_2 in oil

After 600 days switch from seawater to LowSal

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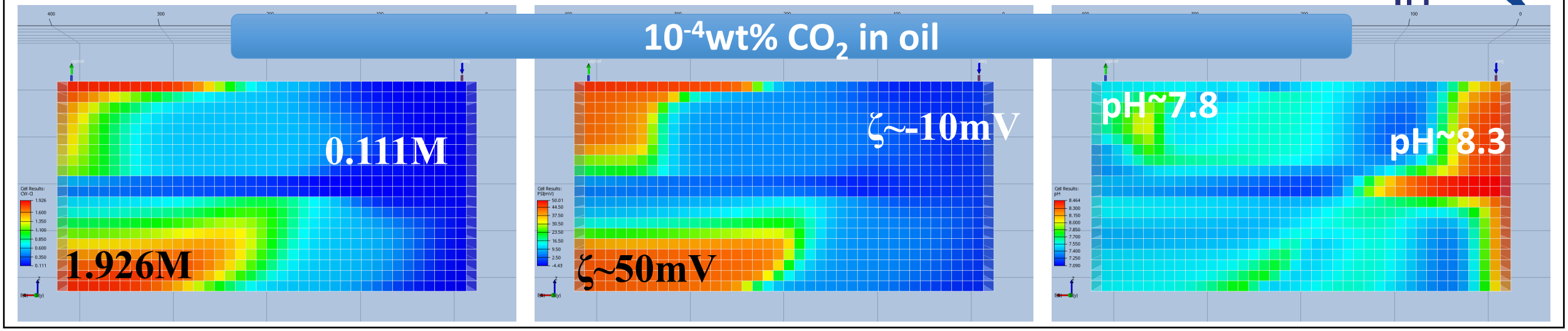
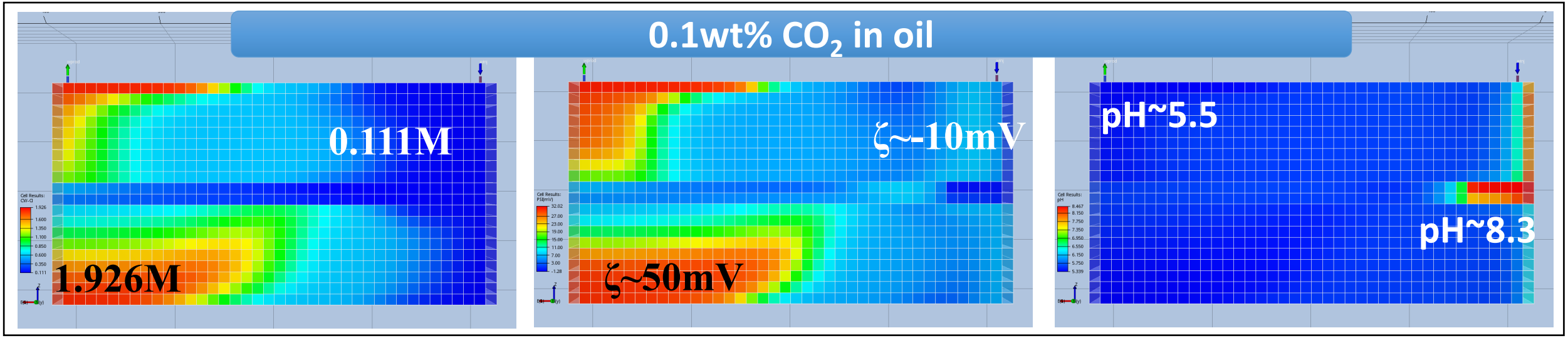
Chlorine Concentration

Surface Potential

pH

(IORCoreSim results)





(900days) pH, salinity and surface potential - different speeds

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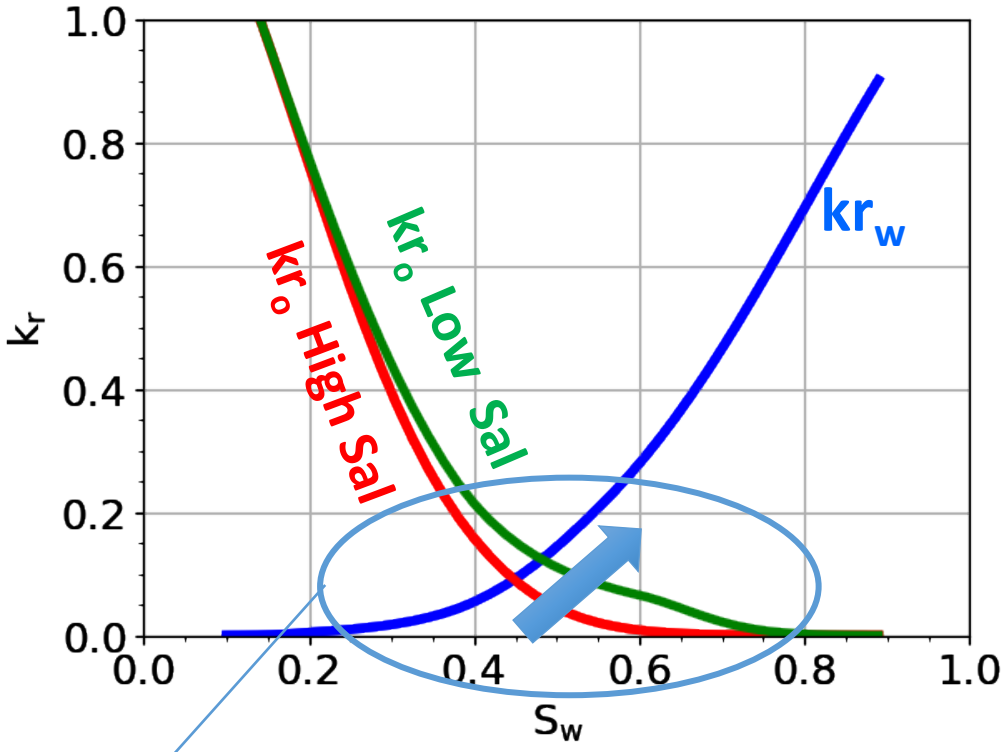
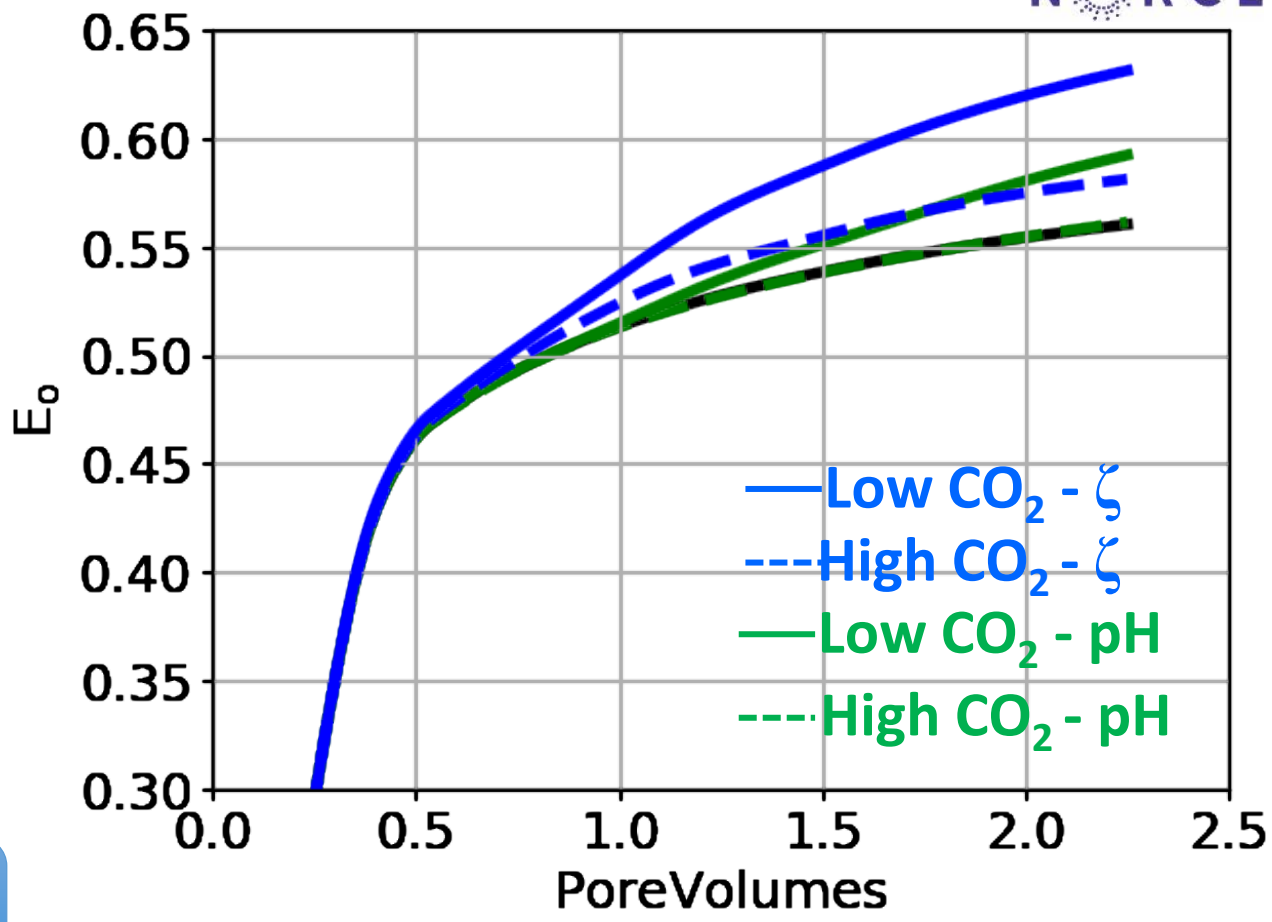
Field Recovery is dependent on mechanism





Case I: pH
Case2: Surface Potential (ζ)

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IORSim Workflow:

ECLIPSE

- Run > eclipse.exe CASE.DATA
- Wait for ECLIPSE to finish

IORSim

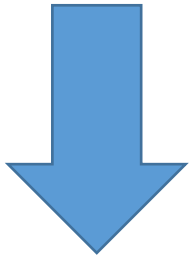
- Run >iorsim.exe CASE
- Wait for IORSim to finish

Vizualize

- FlowViz/Office/ResInsight for grid data
- Well data stored in CASE_W_<well_name>.trcconc (csv format)

A Note on the Input files

- IORSim flow models developed at IFE
- Geochem and Silicate models at NORCE



- Input files have been developed and extended as needed
- Hence, there are some non-logical issues that have to be corrected
  - Some we know of … but we would like feed back from you

CASE.trcinp

```
*TEMPERATURE

*GRIDPLOT_WRITE
*GRIDPLOT_FILE FORMATTED

*N_TRACER
  0

*REACTING_SYSTEM /

*TRACER_LGR

# n_lgr
    0

*INTEGRATION
Comment starts with '#'
#  tstart  tstop
   0.0  1.e99
#  0.0  2.0

#  dtmin dtmax
   0.0   1.e99

#  dteclmin dteclmax
   10 10

# metnum
  0

solver sparskit2
```

```
solver sparskit2

*integrate_species

*MODELTYPE GeoChem

*SPECIES H
*SPECIES Ca
*SPECIES Mg
*SPECIES Cl
*SPECIES HCO3
*SPECIES Na
*SPECIES SO4
*SPECIES K
*SPECIES Ba
*SPECIES Sr

_Mg 1 12 1.e-4 1.e-3

#
# Only one model template incl
# ----------------------------

*MODELTEMPLATE Comp1


*TINIT 130.0

#  cpWat cpOil  cp Gas  cpRock
    4.0   2.0     1.0    1.0

#  roWat roOil  ro Gas  roRock
  1000.0 800.0  400.0   2500.0
```

Species

Used for Low sal back-coupling

```

*COMP 0.0  0.0 0.0  0.0 0.0 0.0 0.0 0.0 0.0 0.0

#                Name      IndxLow      IndxHigh
*MODELINSTANCE   Comp1       1   56  1  73   1   22

*WELLSPECIES

#   Ninjwell
      1

#   Wellname
     I1

#   Ntime
      1

#   Inj    Comp:
#   Time    H    Ca      Mg     Cl     HCO3  Na    SO4     K    Ba Sr    Temp
    0       1. 0.013   0.0445 0.525 0.002 0.45 0.024 0.01 0  0     25.0

*OUTPUT
2
P1
P2

*wellplot_interval
0.0 0.01 /

*END
```

Species in reservoir
Defined in geocheminp
"place holder"

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CASE.geocheminp

```
internal
solution 0
      pH 7
      Ca 0.0999
      Mg 0.021885
      Cl 1.4231
      HCO3 0.002
      Na 1.1428
      SO4 1e-5
      K 0.0073
      Ba 0.00184
      Sr 0.0085
  / end
rate
# rate = (k_1*exp(-Ea/Rg)(1/T-1/298.15)+k_2*exp(-Ea/Rg)(1/T-1/298.15)*(1-SI^n)^m
#mineral   wt-fraction  Sg log_af logEa_1 k_1 logEa_2 k_2       n   m
calcite     38.454      1   0    37.8 3.43E-02   8.4 1.11E+03    1   1
magnesite   0.0         1   0    60  .7E-08      0.0 0.0         1   1
anhydrite   0.0         1   0    60   7E-08      0.0 0.0         1   1
barite      0.0         1   0    30.8 1.11E-03   0.0 1.11E-03    1   1
/ end
```

pH determined by solver, pH=7 is “initial guess for solver”

Reservoir species

```
#iexchange
#X 0.01
#/ end
#method 0 set surfac
#method 1 include su
#method 2 same as 1,
complex
method 2
GCa 1e-3
GCO3 1e-3
/ end
#row 1 to 6 /* Set i
#row 1
solution 1
      pH 7
      Ca 0.013
      Mg 0.0445
      Cl 0.525
      HCO3 0.002
      Na 0.45
      SO4 24e-3
      K 0.01
      Ba 0
      Sr 0
/  end
/end
```

Ion exchange

Surface charge

Injected species “place holder”

$$\frac{\partial c_i(t)}{\partial t} = \sum_i \xi_{ij} I_j, \qquad I_j = sgn(1-\Omega_j)(k_1 + k_2 a_H)\left|1-\Omega_j^m\right|^n.$$

$$k_1 = k_{10} e^{\frac{E_{a1}}{R}\left(\frac{1}{298.15}-\frac{1}{T}\right)}, \; k_2 = k_{20} e^{\frac{E_{a2}}{R}\left(\frac{1}{298.15}-\frac{1}{T}\right)}.$$

https://pubs.usgs.gov/of/2004/1068/pdf/OFR_2004_1068.pdf

USGS science for a changing world

A COMPILATION OF RATE PARAMETERS OF WATER-MINERAL INTERACTION KINETICS FOR APPLICATION TO GEOCHEMICAL MODELING

U.S. GEOLOGICAL SURVEY

OPEN FILE REPORT 2004-1068

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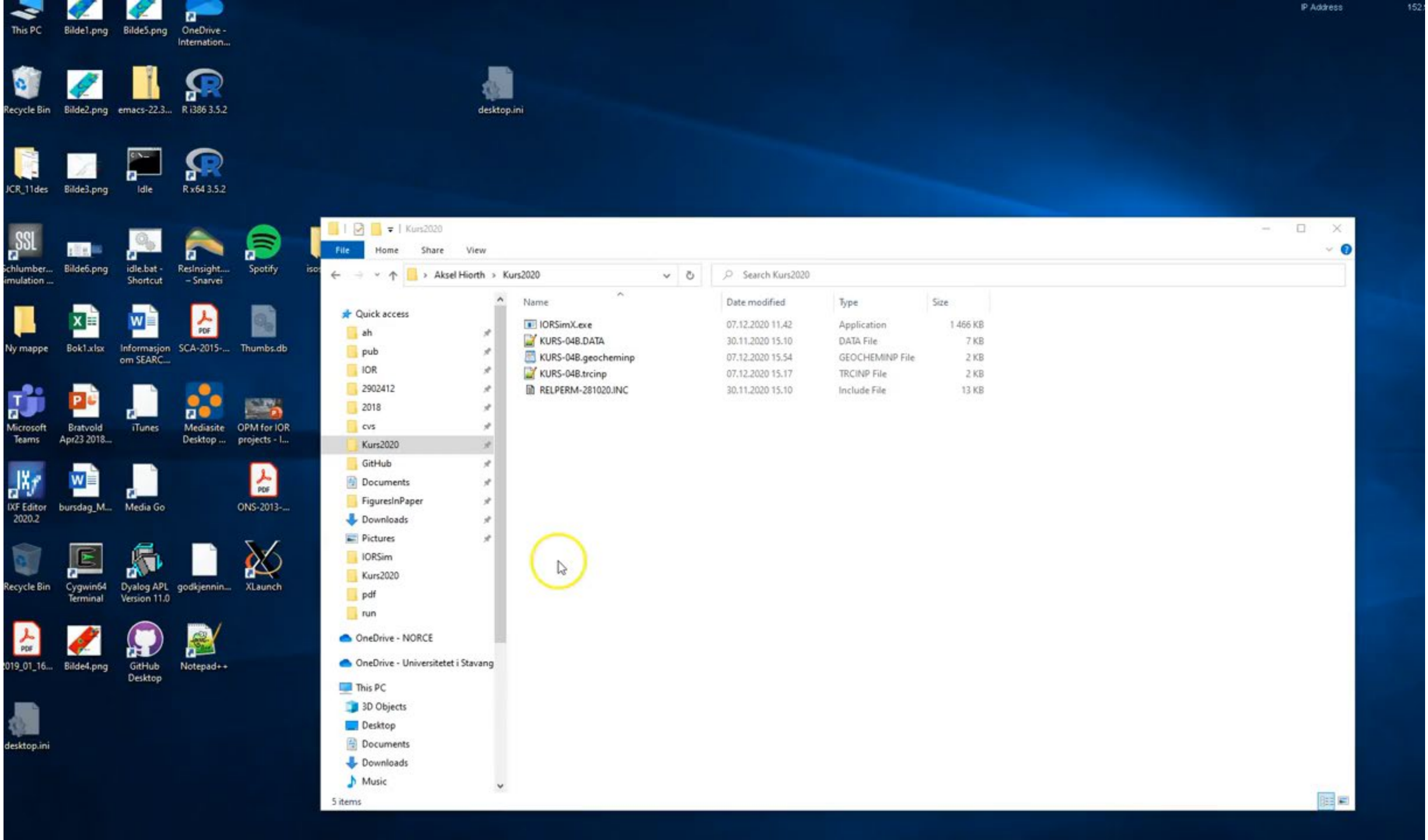
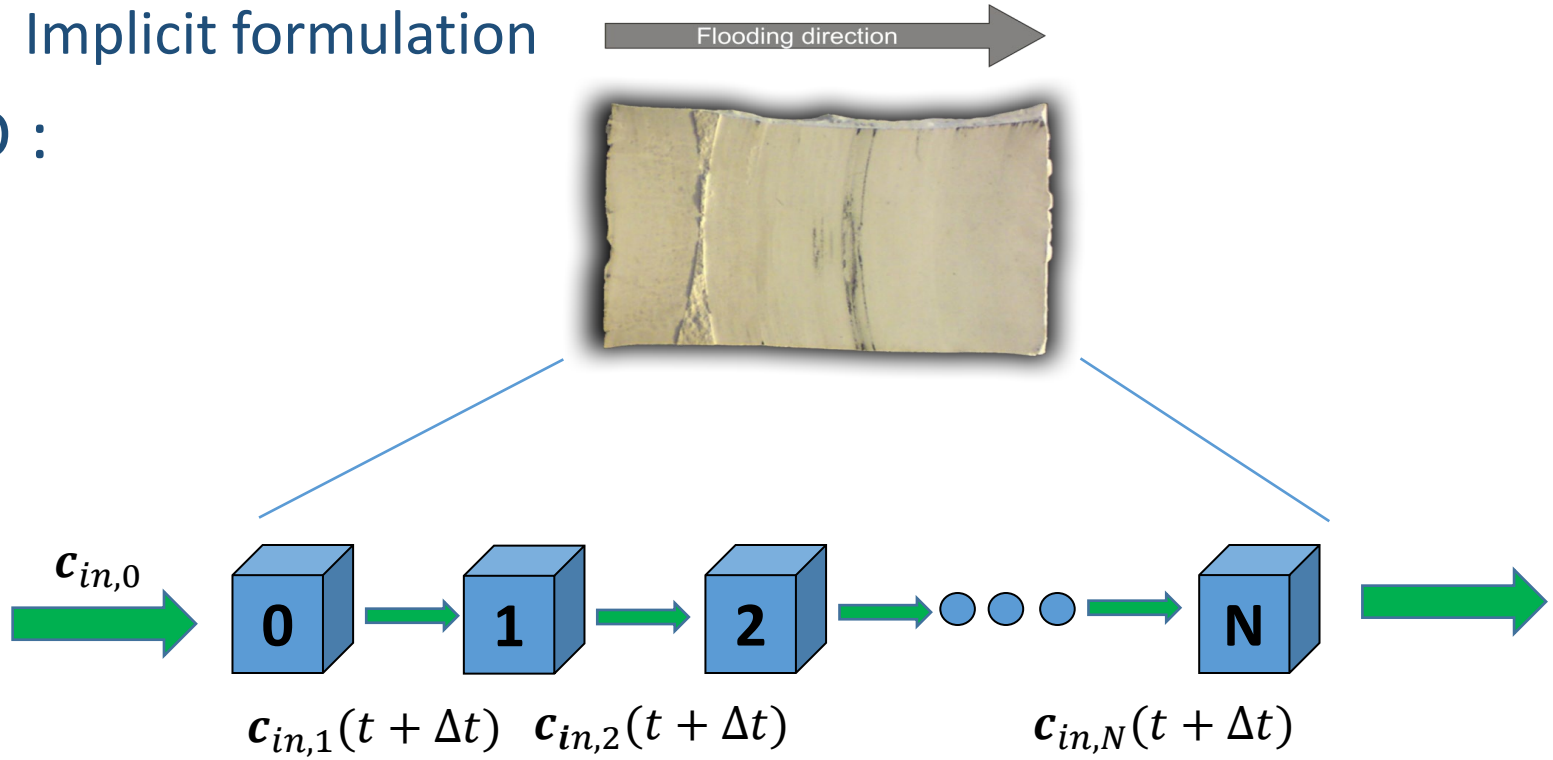

This PC
Bilde1.png
Bilde5.png
OneDrive - Internation...
Recycle Bin
Bilde2.png
emacs-22.3...
R i386 3.5.2
desktop.ini
JCR_11des
Bilde3.png
Idle
R x64 3.5.2
Schlumber... imulation ...
Bilde6.png
idle.bat - Shortcut
ResInsight.... – Snarvei
Spotify
Ny mappe
Bok1.xlsx
Informasjon om SEARC...
SCA-2015-...
Thumbs.db
Microsoft Teams
Bratvold Apr23 2018...
iTunes
Mediasite Desktop ...
OPM for IOR projects - I...
IXF Editor 2020.2
bursdag_M...
Media Go
ONS-2013-...
Recycle Bin
Cygwin64 Terminal
Dyalog APL Version 11.0
godkjennin...
XLaunch
2019_01_16...
Bilde4.png
GitHub Desktop
Notepad++
desktop.ini
Kurs2020
File
Home
Share
View
Aksel Hiorth › Kurs2020
Search Kurs2020
Quick access
ah
pub
IOR
2902412
2018
cvs
Kurs2020
GitHub
Documents
FiguresInPaper
Downloads
Pictures
IORSim
Kurs2020
pdf
run
OneDrive - NORCE
OneDrive - Universitetet i Stavang
This PC
3D Objects
Desktop
Documents
Downloads
Music
Name
Date modified
Type
Size
IORSimX.exe
07.12.2020 11.42
Application
1 466 KB
KURS-04B.DATA
30.11.2020 15.10
DATA File
7 KB
KURS-04B.geocheminp
07.12.2020 15.54
GEOCHEMINP File
2 KB
KURS-04B.trcinp
07.12.2020 15.17
TRCINP File
2 KB
RELPERM-281020.INC
30.11.2020 15.10
Include File
13 KB
5 items

BACKUP

A modular interface:

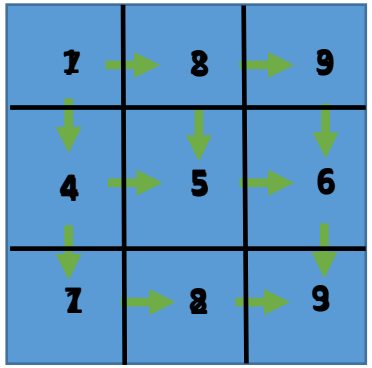
- Advection calculations separate from reactions
  - Implicit formulation
- 1D :



Block-by-block upstream integration

Can we extend to 3D?

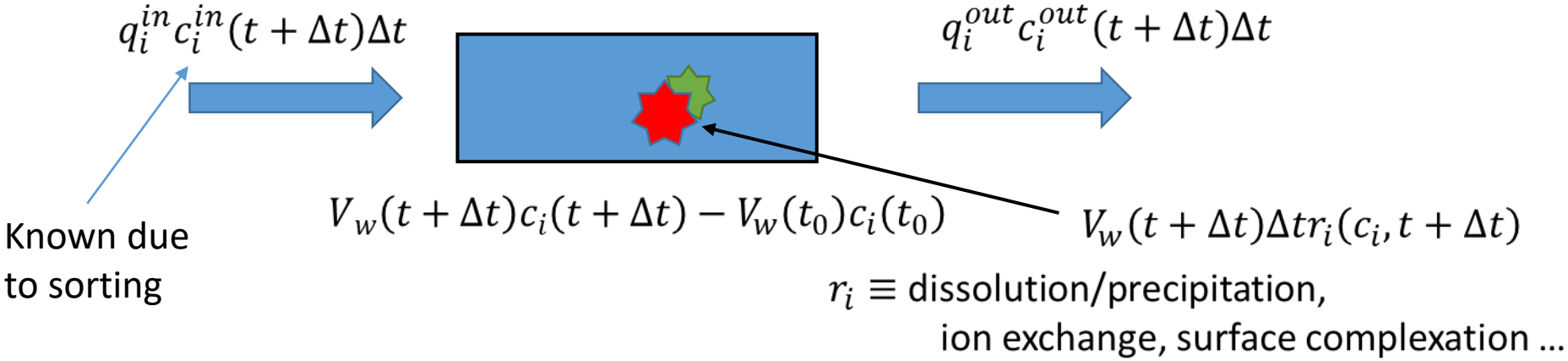
- Yes, if there are no flow loop (tear up the loop)
- 3x3 Example



- Renumbering of ECLIPSE grid
  - implicit integration of the concentrations if no flow loops are detected
  - If flow loops, an explicit coupling is inserted to tear the flow loop
  - The algorithm is fast (O(N))

The IORSim methodology on a complex computational problem:

- Fast full geochemical calculations
- Robust, efficient solution:
  - Transport and geochemistry solved **separately** and **implicit**
    - Global level (Flow) & Local (Block) level (non-linear physics chemistry)
  - Decompose reservoir into separate flow paths
  - Flow path is solved on a block sequentially:



IORsim course 10.12.20

Plan

1) Introduction – B. Antonsen
2) IORSim general & tracer – J. Sagen
3) I. Geochemistry – A. Hiorth
4) I. Backward; Silicate – B. Antonsen
5) Demo I. Backward – J.L. Vinningland
6) Feedback

Helpdesk 11.12.20 10-12 J.L. Vinningland,
javi@norceresearch.no

IORSim course		
Andrea Johanne Reinholdtsen	Accepted	Neptune Energy
Reza Rostami Ravari	Accepted	Neptune Energy
Soujatya Mukherjee	Accepted	Wintershall-DEA
Kristian Eide-Engdahl	Accepted	Lundin
Carl Joerg Petersen	Tentative	Wintershall-DEA
Udo Zimmermann	Accepted	UiS
Ove Sævareid	Tentative	NORCE
Kjersti Riiber	Accepted	UiS
Robert Moe	Accepted	ConocoPhillips
Egil Boye Petersen	Accepted	AKER BP
Gaël Chupin	Tentative	Lundin
Aksel Hiorth	Accepted	UiS
Jan Sagen		IFE
Børre Jacob Antonsen	Accepted	IFE
Jan Ludvig Vinningland	Accepted	NORCE
Jan Nossen	Accepted	IFE

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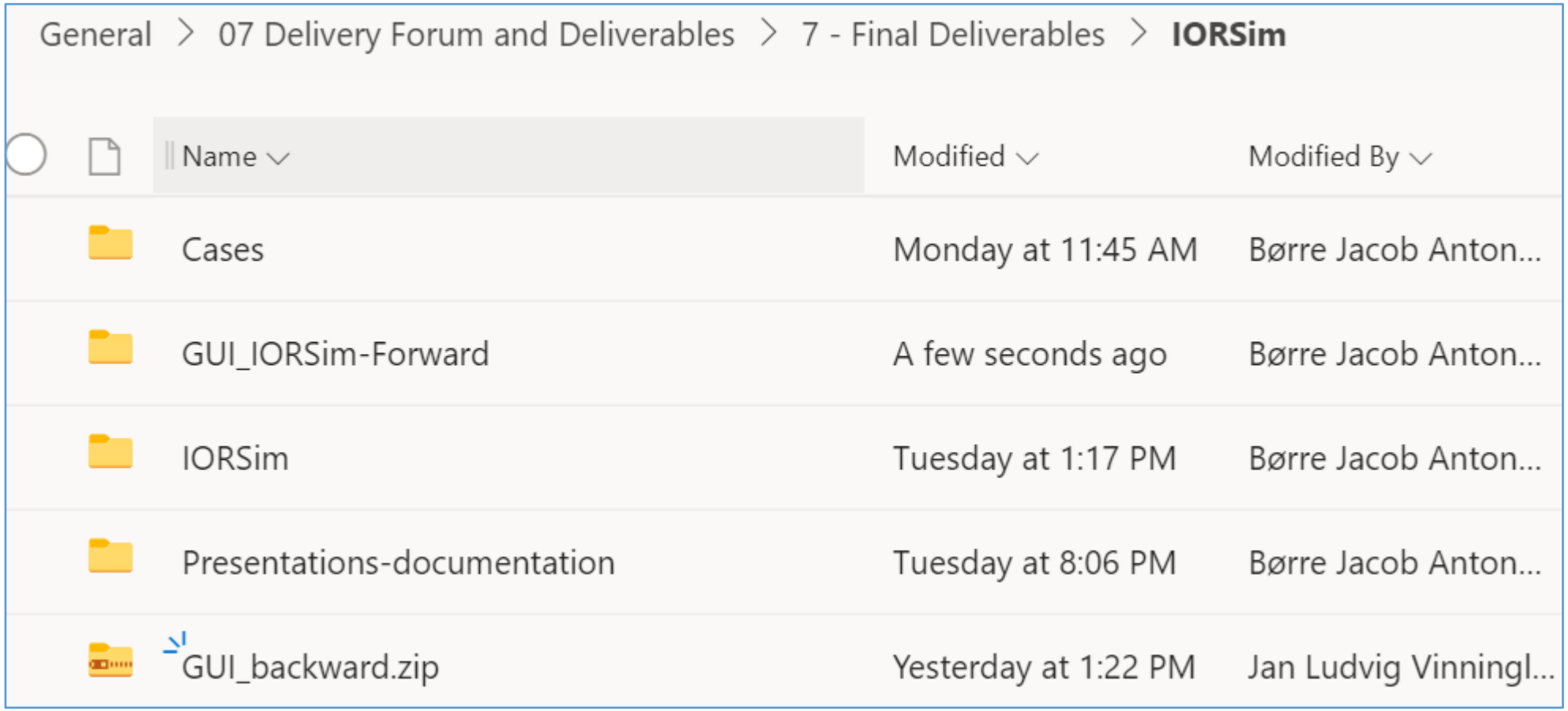
IORSim at Teams at UIS/IOR Centre



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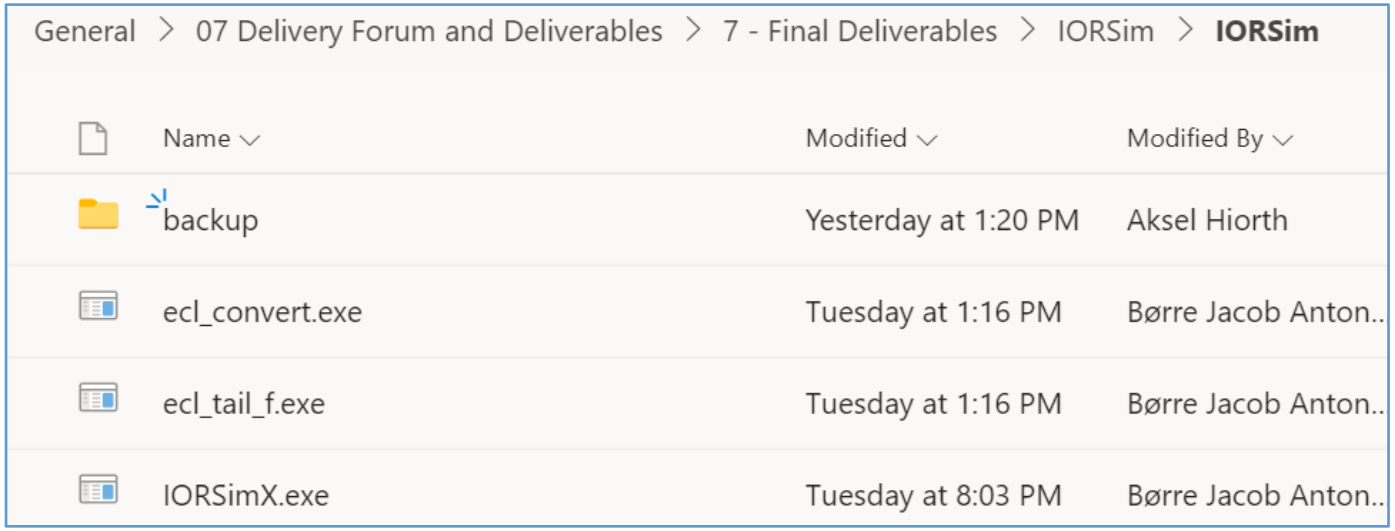
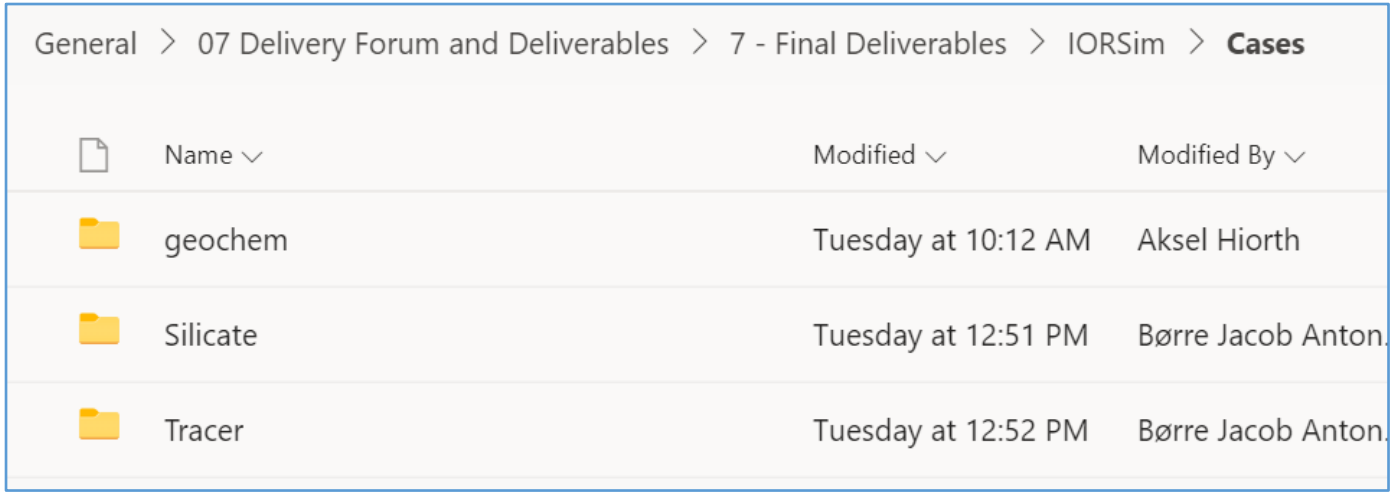
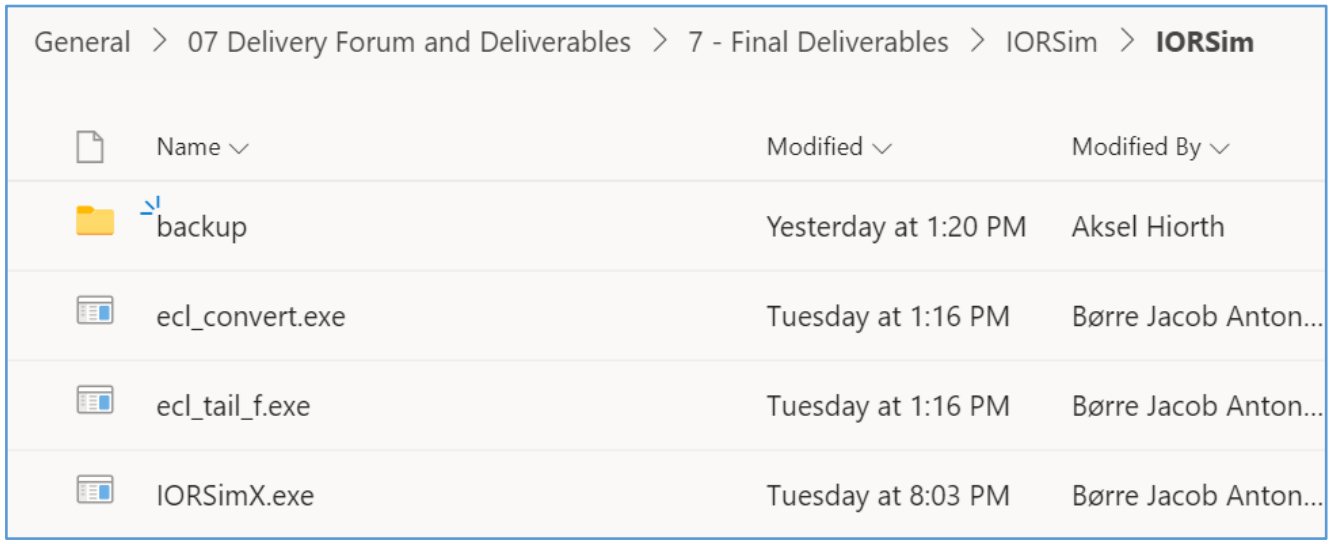
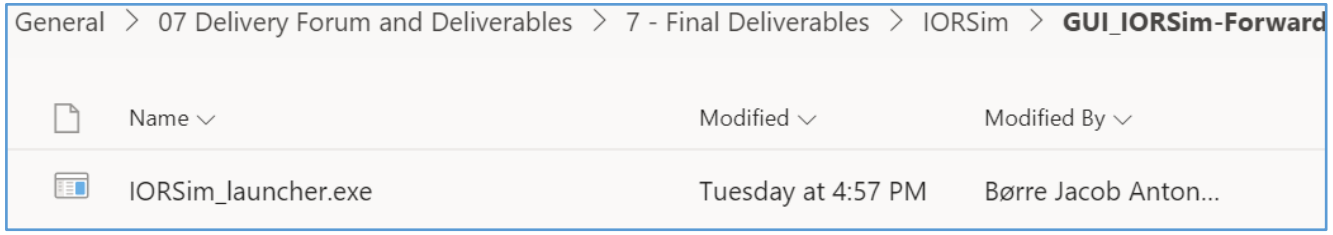
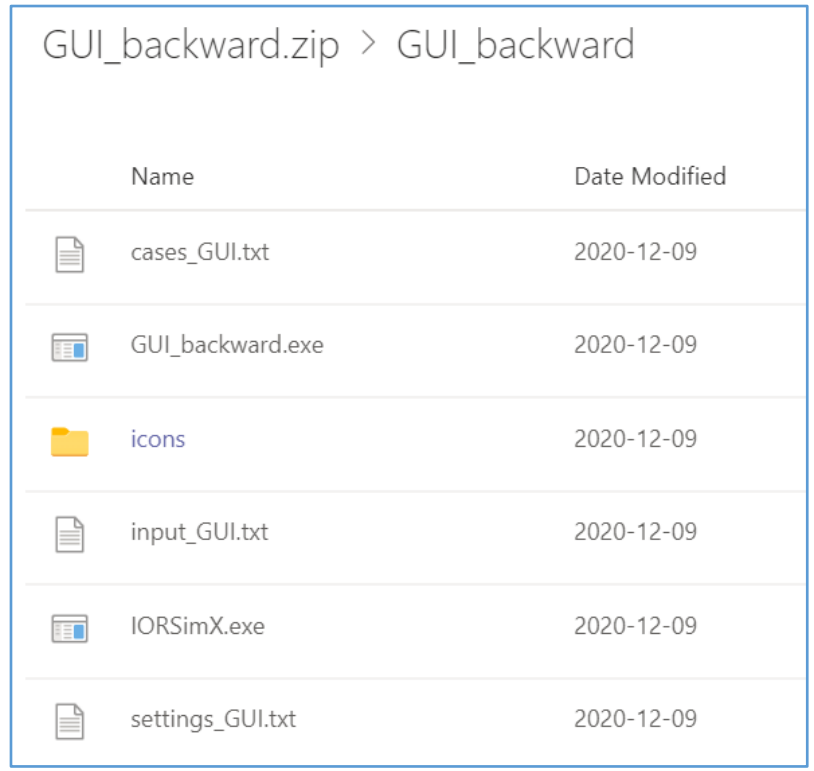




IORSim at Teams at UIS/IOR Centre







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IORsim for your simulation models

Name	Date modified	Type
KURS-04B	09.12.2020 ...	DATA File
KURS-04B.EGRID	09.12.2020 ...	EGRID File
KURS-04B	09.12.2020 ...	GEOCHEMINP File
KURS-04B.INIT	09.12.2020 ...	INIT File
KURS-04B	09.12.2020 ...	RFT File
KURS-04B	09.12.2020 ...	TRCINP File
KURS-04B.UNRST	09.12.2020 ...	UNRST File

```
#                Name      IndxLow      IndxHigh
#*MODELINSTANCE  Comp1       1 1 1 1    1  50
*MODELINSTANCE  Comp1       1   56  1  73   1   22

*WELLSPECIES

#   Ninjwell
      1

#   Wellname
     I1

#   Ntime
      1

#   Inj   Comp:
#   Time    H    Ca      Mg     Cl     HCO3  Na    SO4    K    Ba Sr   Temp
    0       1. 0.013   0.0445 0.525 0.002 0.45 0.024 0.01 0  0    25.0

#*DT        1.0
#*TMAX      1000.0
#*DTOUT     5.0

*OUTPUT
2
P1
P2
```

KURS-04B.DATA file

```
-- Restart output
RPTRST
'BASIC=2'
ALLPROPS=2
FLOWS
PRES
/
WRFTPLT
   I1         NO REPT /
   P1         NO REPT /
   P2         NO REPT /
--   'OBS'      NO REPT /
/
```

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IORSim Backward

10.12.20 B. Antonsen

IORSim Backward

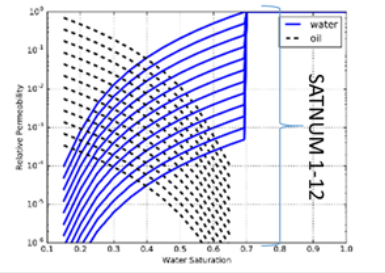
- IORSim Backward modus interacts with Eclipse at every report-timestep.
- It can be used for simulation of water diversion with injection of sodium silicate.
- IORSim calculates the generation and location of silicate gel resulting in reduced permeability.
- The permeability is dynamically updated in the Eclipse model by reduced relative permeabilities (SATNUM).

IORSim - A Simulator for Fast and Accurate Simulation of Multi-phase Geochemical Interactions at the Field Scale

By A. Hiorth, J. Sagen, A. Lohne, J. Nossen, J.L. Vinningland, E. Jettestuen and T. Sira

Publisher: European Association of Geoscientists & Engineers

Source: Conference Proceedings, ECMOR XV - 15th European Conference on the Mathematics of Oil Recovery, Aug 2016, cp-494-00142



KRYSTAZIL 40 (Vannglass) Side 1 av 4

SIKKERHETSDATABLAD
KRYSTAZIL 40 (Vannglass)

ikkerhetsdatabladet er i samsvar med Kommisjonsforordning (EU) 2015/830 av 28 mai 2015 om endring av europaparlaments- g rådsforordning (EF) nr. 1907/2006 om registrering, vurdering, godkjenning og begrensning av kjemikalier (REACH)

. Identifikasjon av stoffet / produktet og av selskapet / foretaket

ltgitt dato	15.01.2003
jemikaliets navn	KRYSTAZIL 40 (Vannglass)
jemisk navn	Natriumsilikat
ynonymer	Vannglass
ITN-nr.	70311800011206
IOBB-nr.	20002329, 28139210
ormel	Na2SiO3
jemikaliets bruksområde	pH-REGULERENDE MIDLER

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Gels used in field operations

Slide 9

Snorre – Field pilot operation:
June 2013 - October 2013

- 1,5 months Pre-slug: 113 500 m3
  - Desalinated seawater
  - Added concentrated KCl
- 3 months Silicate injection: 240 000 m3
  - Concentrated Silicate
  - Diluted with desalinated water
  - pH adjustment with HCl (diluted from concentrated acid)
- 0,5 month Post-slug: 49 000 m3
  - Desalinated seawater
  - Added concentrated KCl
- Continue water injection from the Snorre platform

Statoil

K. Skrettingland presentation, 2016

More Than 12 Years' Experience With a Successful Conformance-Control Polymer-Gel Technology

R.D. Sydansk, SPE, and **G.P. Southwell,** SPE, Marathon Oil Co.

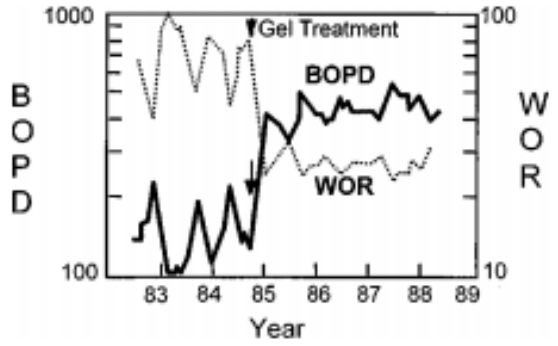

Fig. 1–Production response to the CC/AP gel treatment applied to injector O-7 in the SOB field.

SPE Prod. & Facilities, 2000
1400 gel applications.

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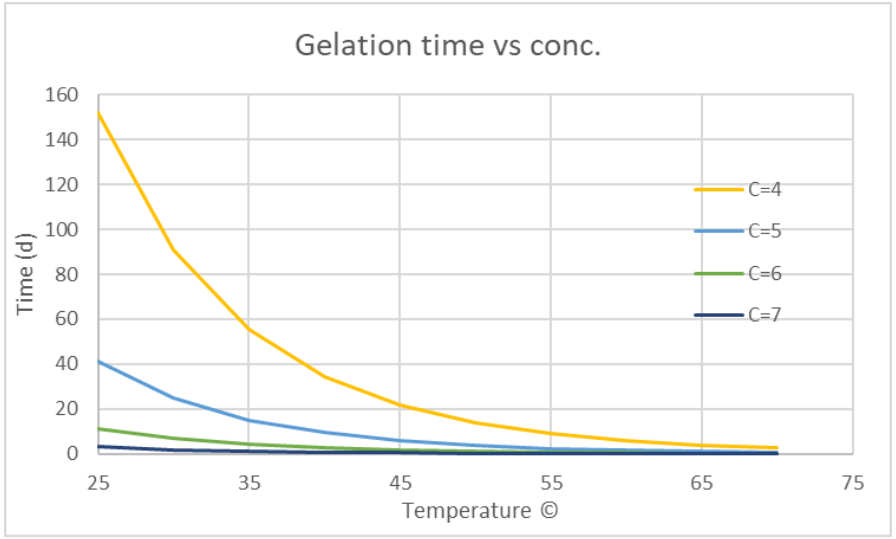
Gelation time

- $t_g = A\, e^{\alpha C\_Si}\, e^{\beta\, C\_HCL} e^{\gamma\ \sqrt{C\_Ca}}\, e^{Ea/RT}$

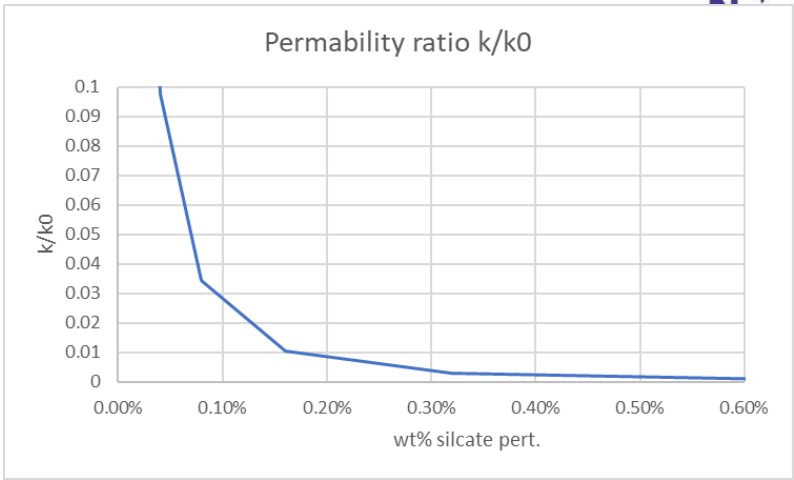
  A= 8.75 10^{-10} days, α=-0.6 1/wt%, β=-0.7 1/wt%, γ=-0.1 1/√ppm, Ea=77kJ/mol

  (From Stavland, Jonsbråthen, Vikane, Skrettingland, Fisher, 2011)



Permeability modification

- $\frac{k}{k_0} = (1 + 275\ Y\ S_w \sqrt{\frac{k_0}{\varphi_0}}\ )^{-2}$



- Y is the weight fraction of sodium silicate precipitated per mass of water.
- Blocking of pores happens when gel conc. is about 0.3 wt% (Based on experiments)
- For “IORSim Backward” permeability modification is transferred as scaling of relative permeability – Eclipse SATNUM is transferred.

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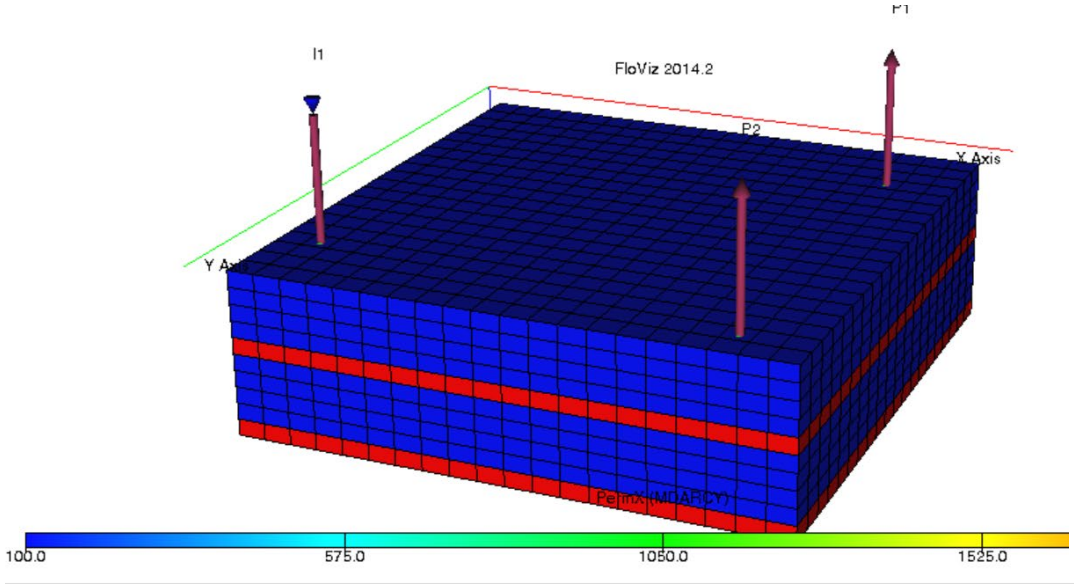
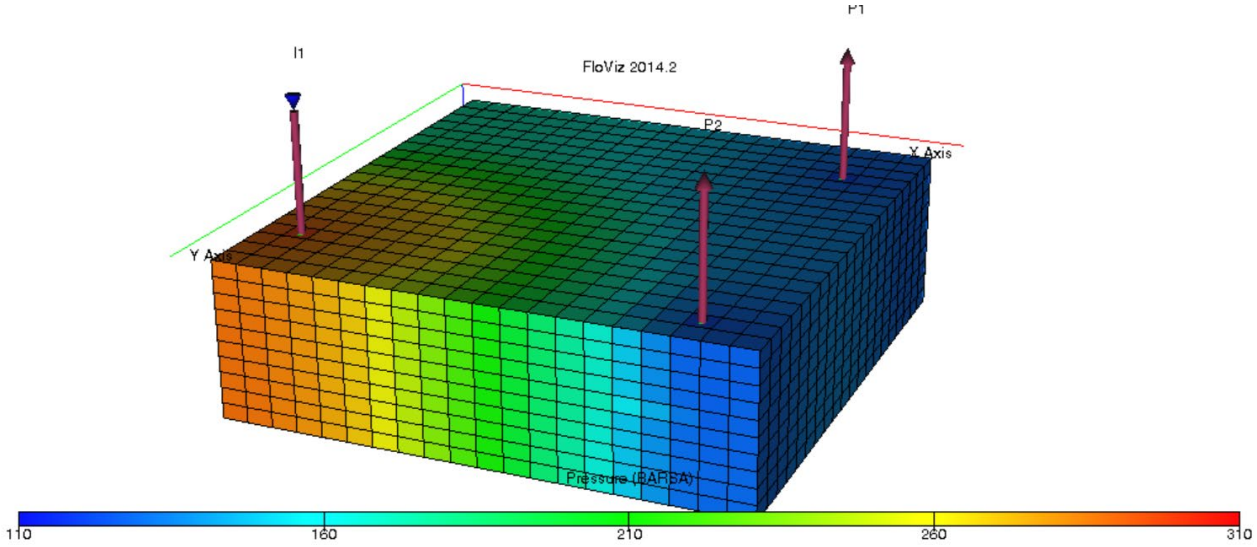
Test model



Permeability



Pressure

Silicate model Input

```
*TEMPERATURE

*GRIDPLOT_WRITE
*GRIDPLOT_FILE FORMATTED

*N_TRACER
  0

*REACTING_SYSTEM /

*TRACER_LGR

# n_lgr
      0

*INTEGRATION

#  tstart  tstop
   0.0  1.e99

#  dtmin dtmax
   0.0  1.e99

#  dtecl dteclmax
     5      20

# metnum
  0

solver sparskit2

*integrate_species

*MODELTYPE SILIKAT

*SPECIES Silica
*SPECIES MobGel
*SPECIES HCl
*SPECIES Ca
*SPECIES ImMobGel
```

```
#
# Model templates
# -------------------------------------

*MODELTEMPLATE Comp1
*TINIT 95.0

#  cpWat cpOil  cp Gas  cpRock
    3.9   2.1     2.1    1.0

#  Water density, test value
#  Oil density, test value
#  Gas density, test value
#  Rock density, test value

#  roWat roOil  ro Gas  roRock
  999.9 800.0  400.0   2350.0

#*COMP 0. 0. 0. 0.4

#              Name     IndxLow IndxHigh IndyLow IndyHigh IndzLow IndzHigh
*MODELINSTANCE  Comp1       1       20    1        20    1       10

*WELLSPECIES

#   Ninjwell
      1

# -------------------------------------
#   Wellname
     I1
#   Ntime
      3
#   Time  Comp
   0.0 0 0 0 0.04089 0 20
   200 5 0 5.0 0. 0 20
   265 0 0 0 0.04089 0 20
# -------------------------------------

#*DT       1.0
#*TMAX     1000.0
#*DTOUT    5.0

*OUTPUT
2                # number of output wells
P1
P2

*wellplot_interval
0.0 0.01 /


END
```

Silicate and HCL

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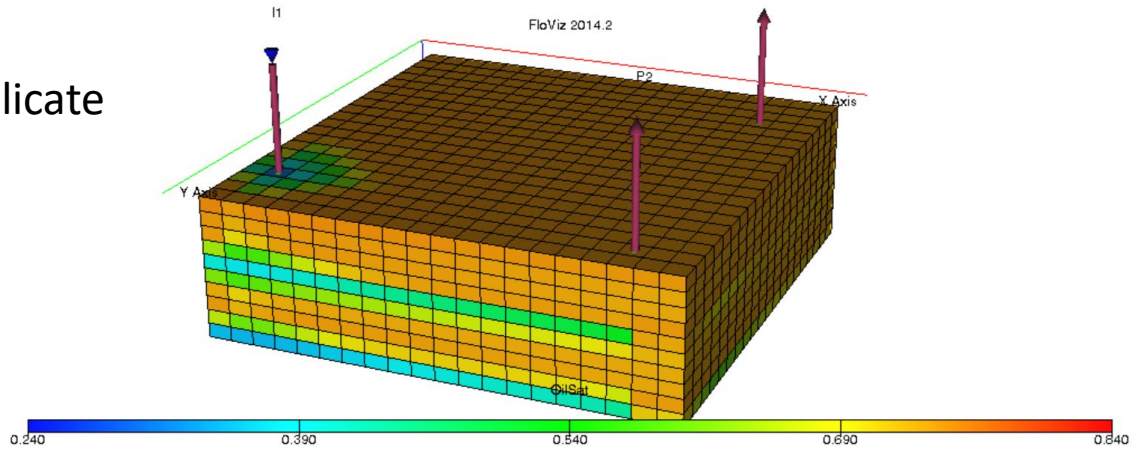
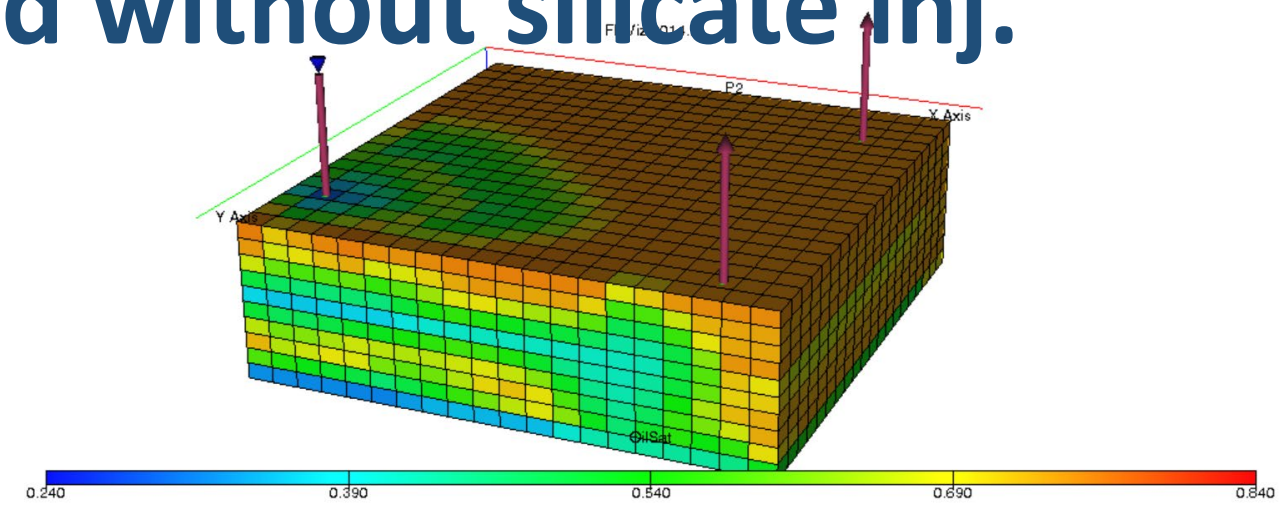
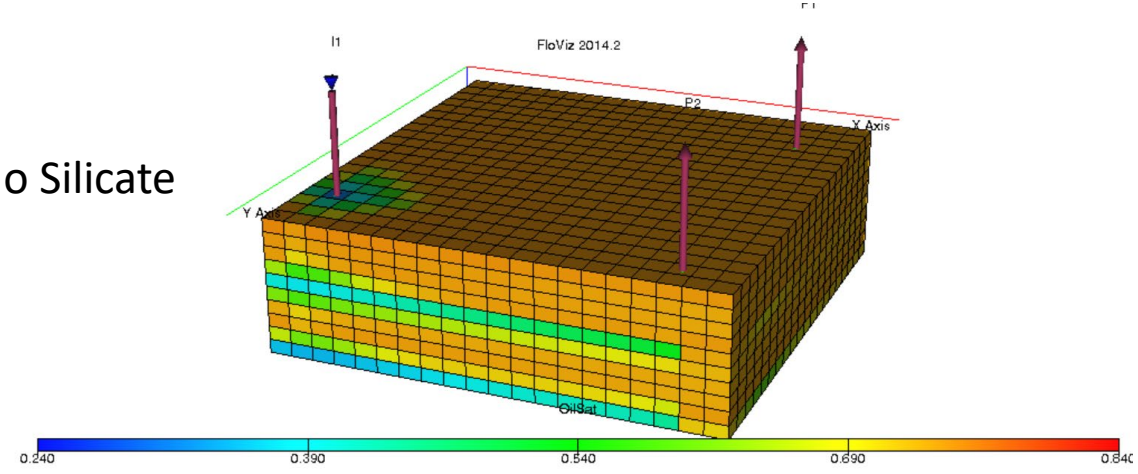
Oil saturation with and without silicate inj.

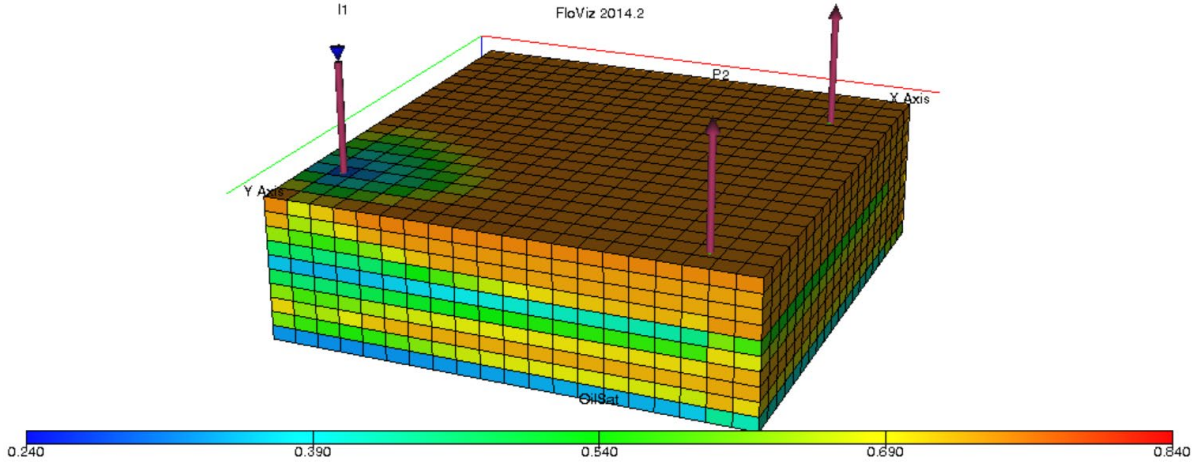
Silicate





No Silicate





Oil after 1y

Oil after 2y

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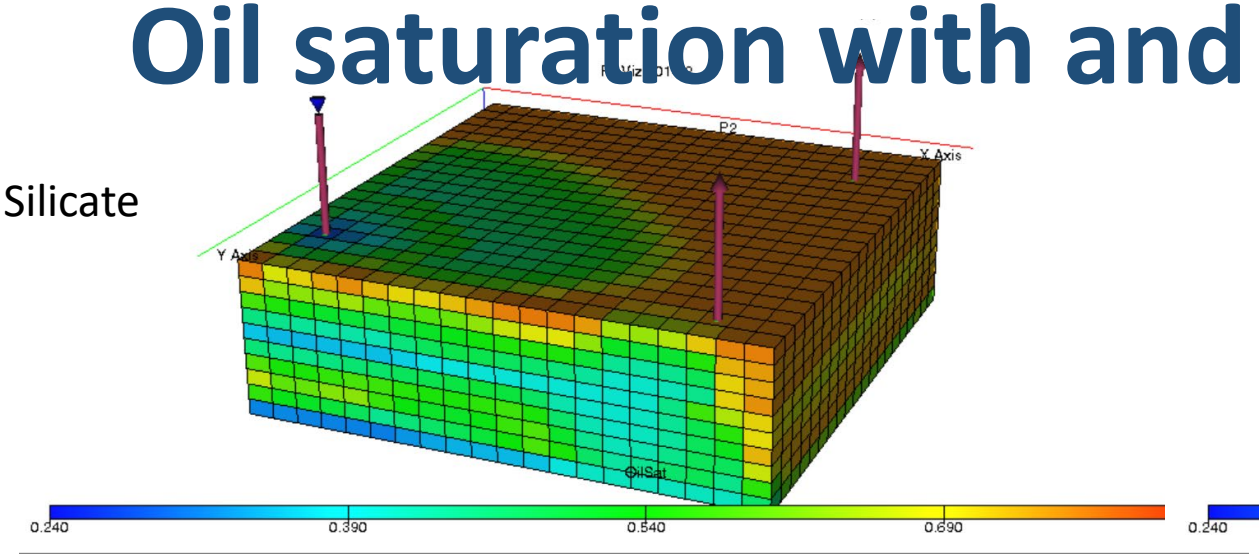
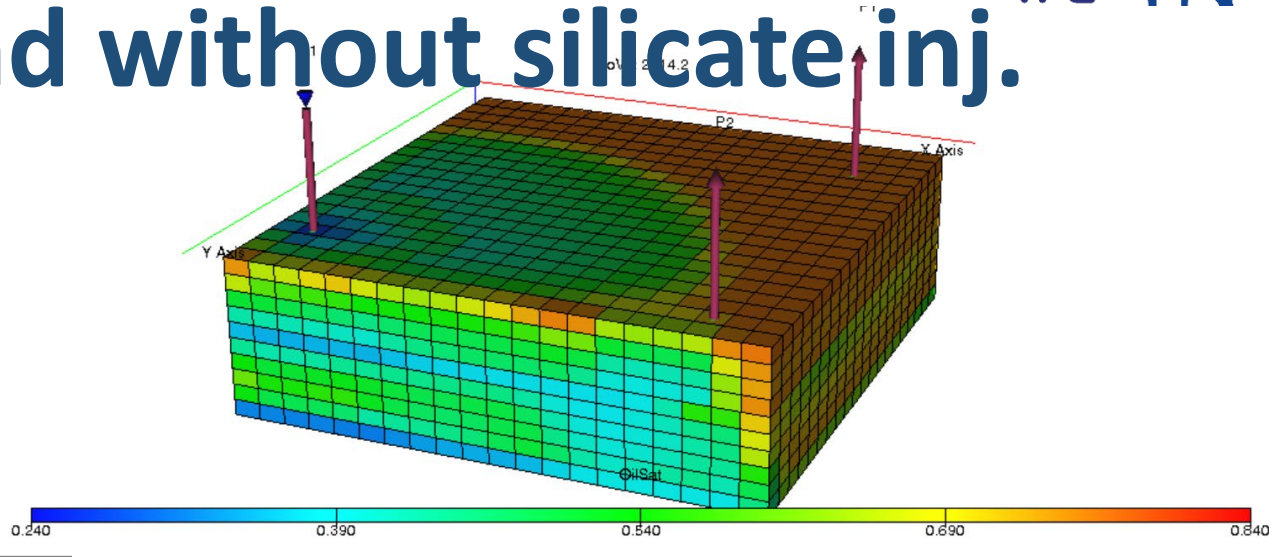
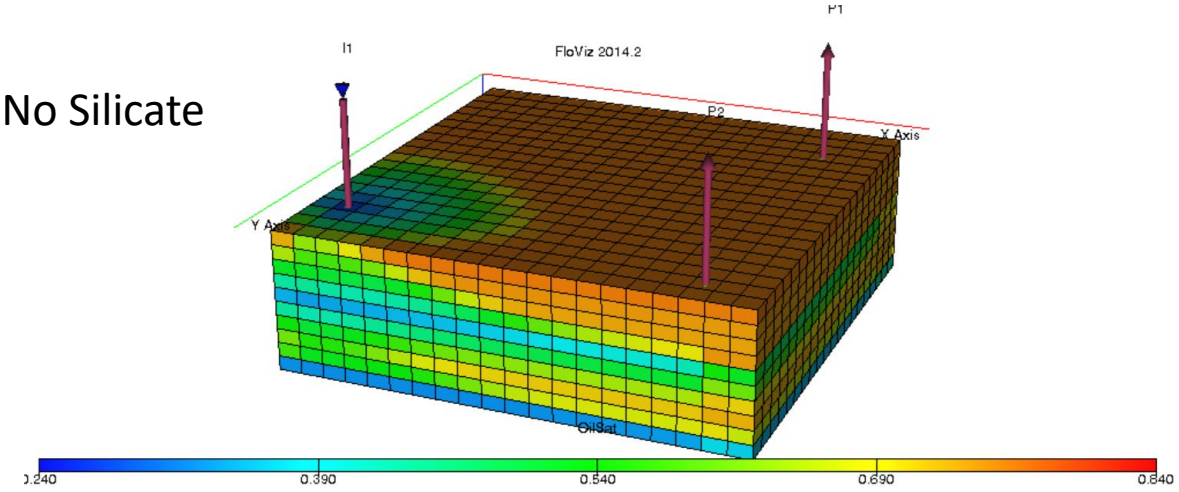
Oil saturation with and without silicate inj.

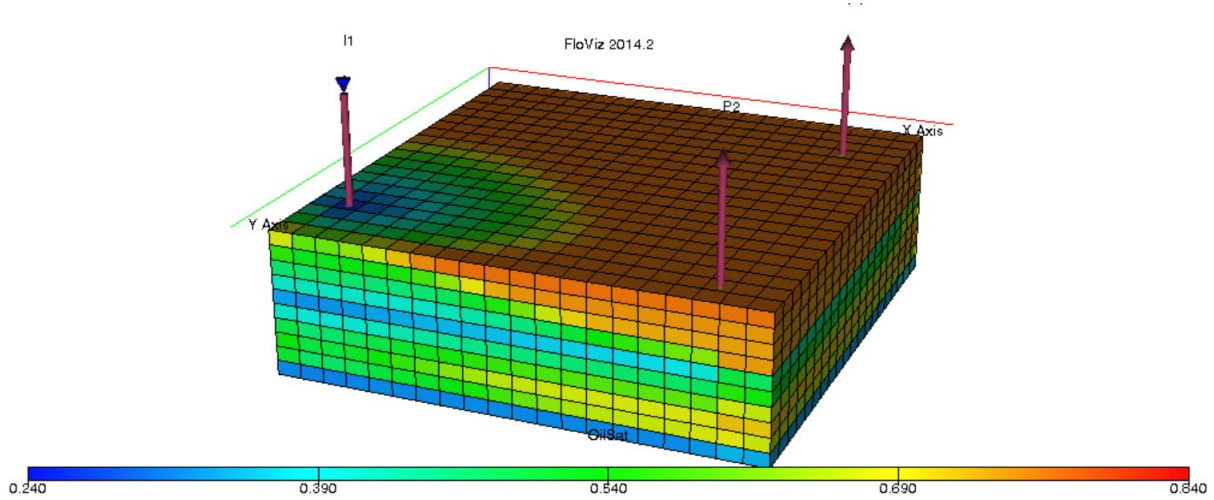
Silicate





No Silicate





Oil after 3y

Oil after 4y

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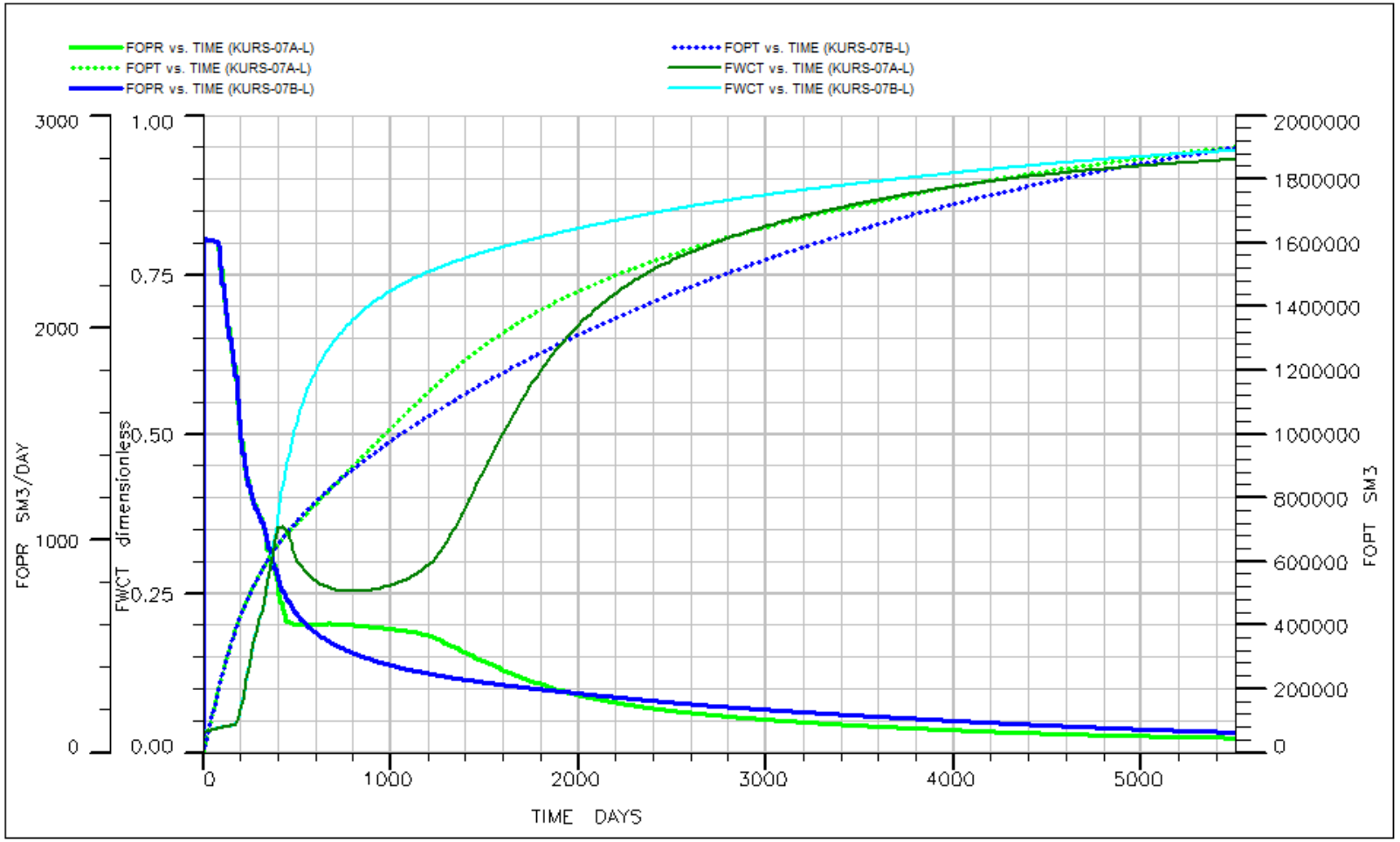
Field production



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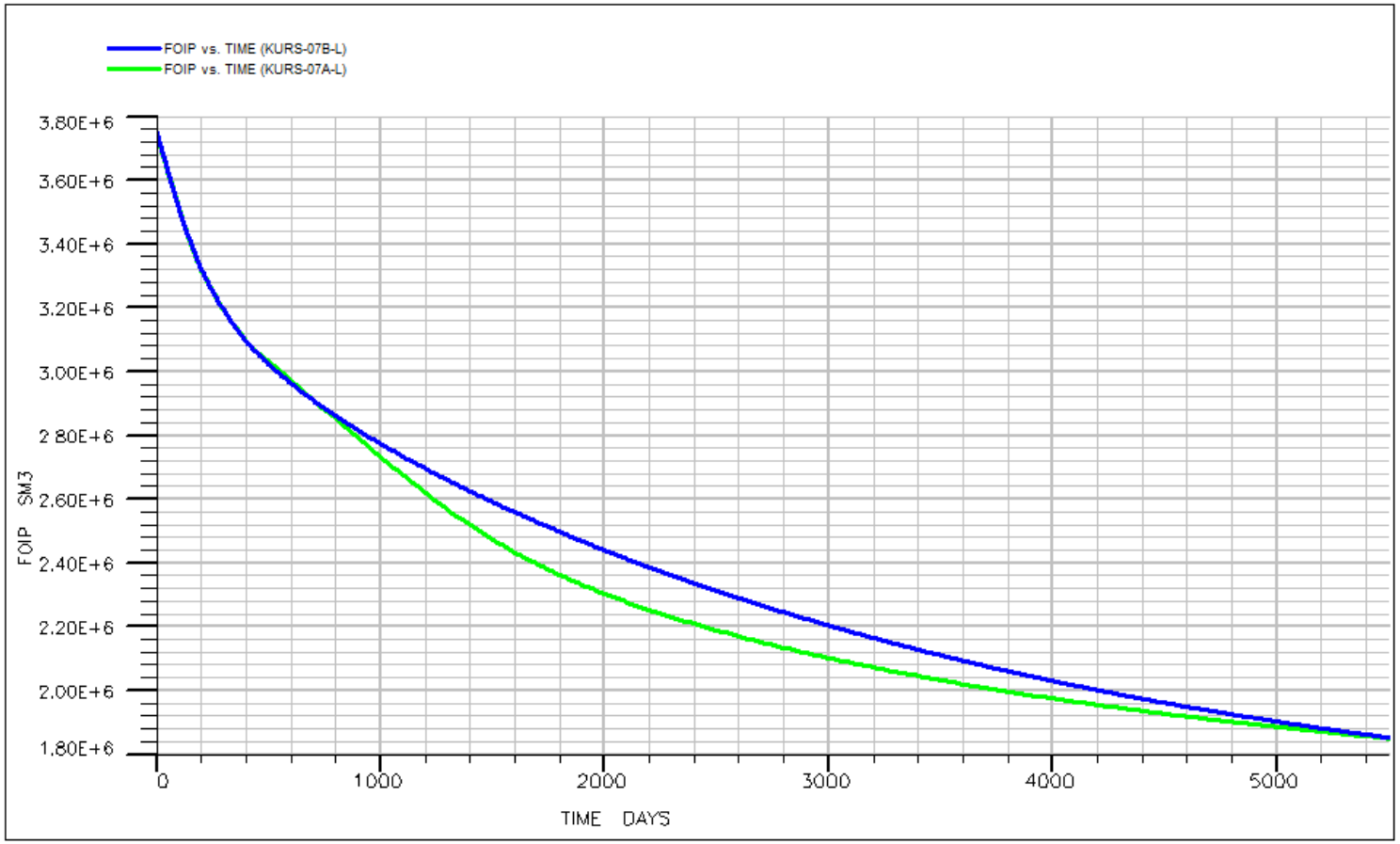
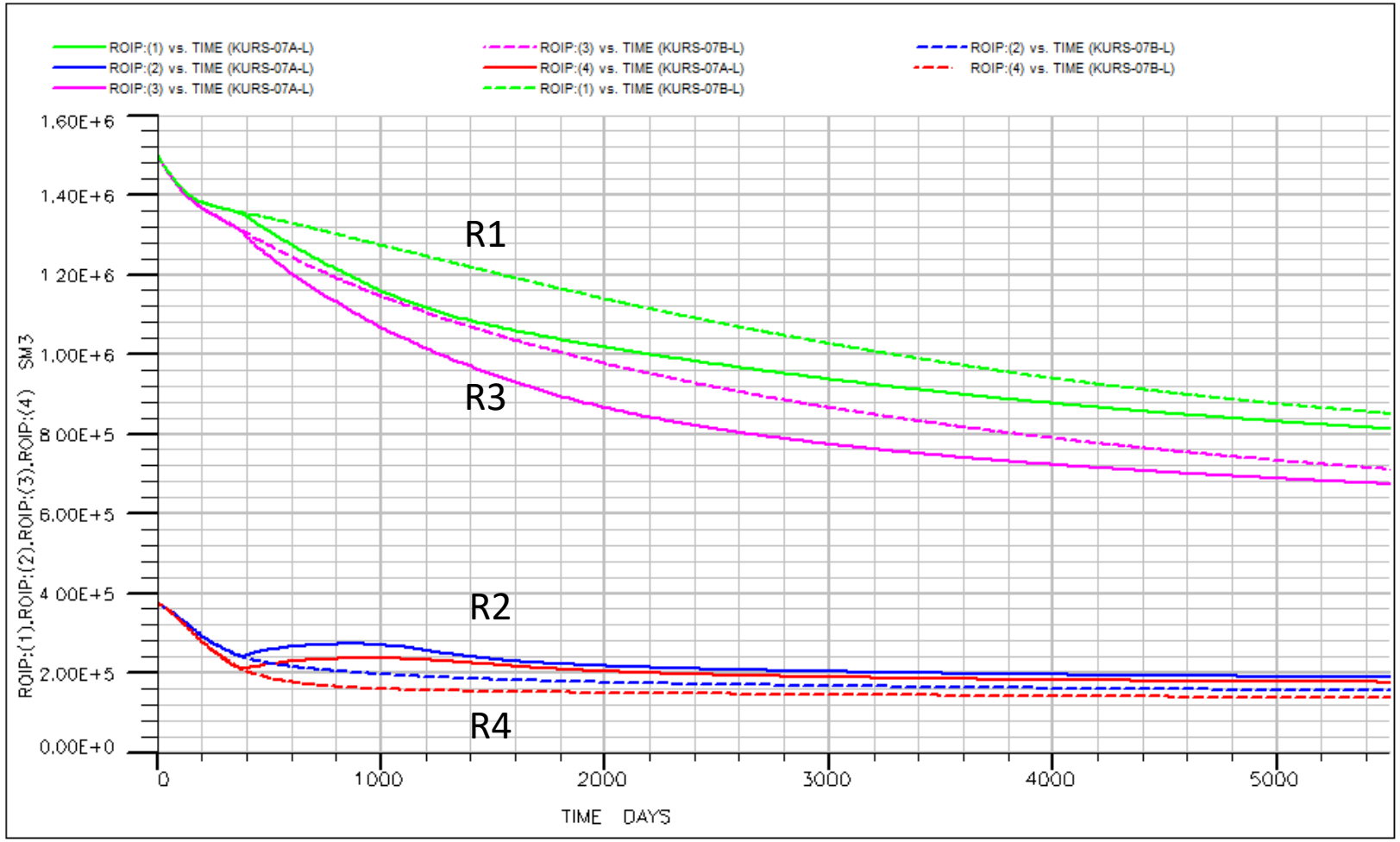
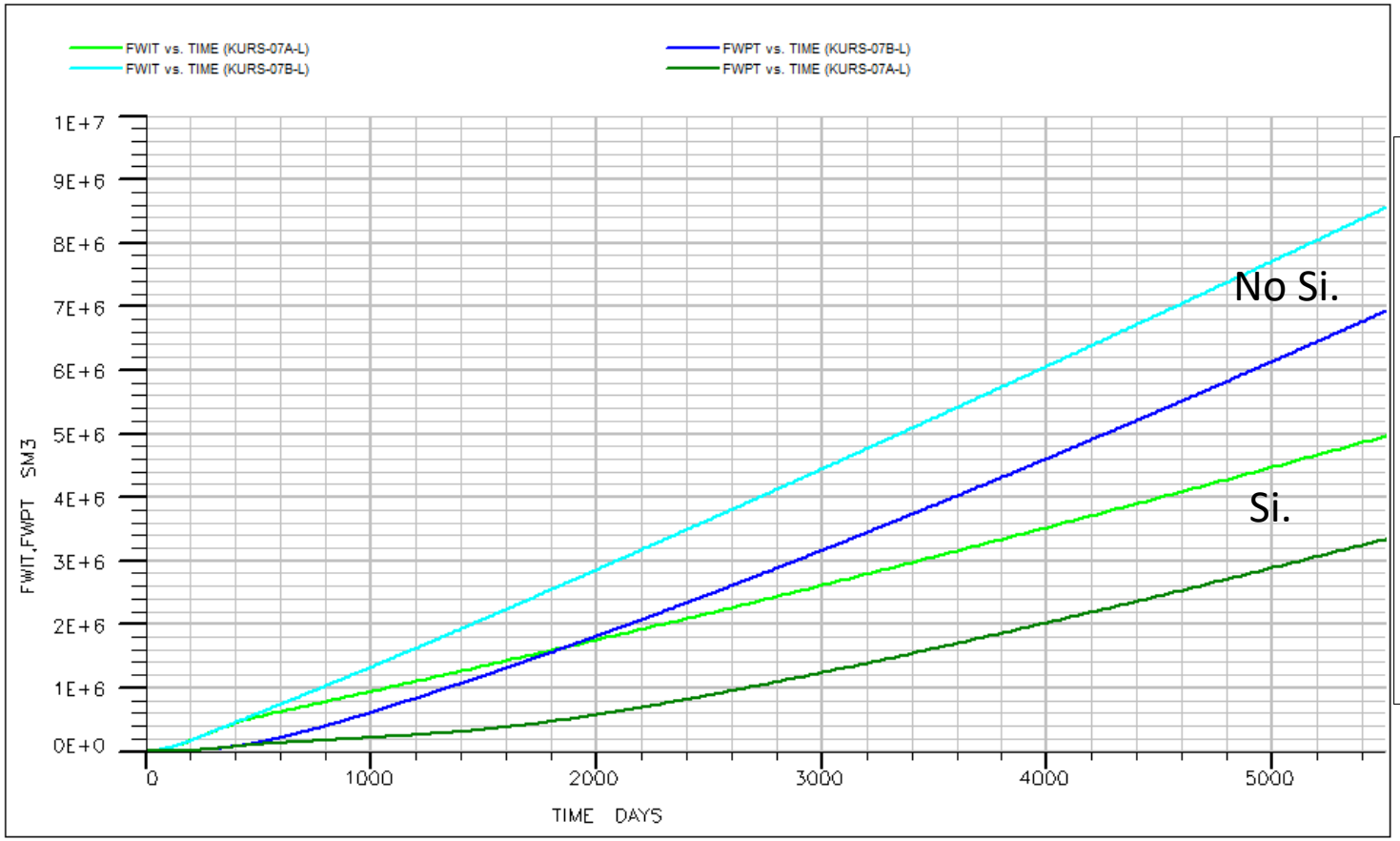
Recovery – remaining oil in-place

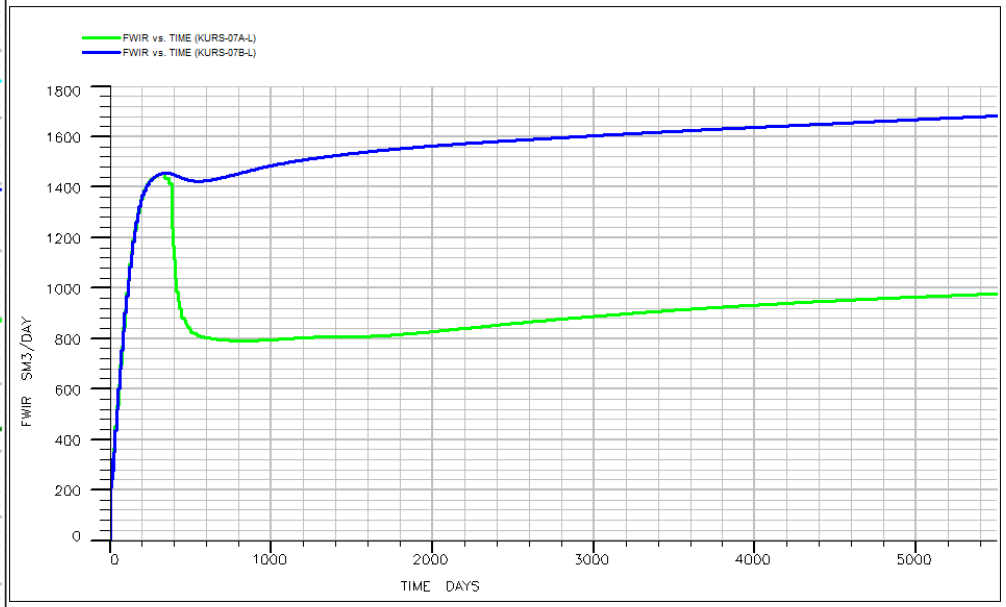


Recovery per layer

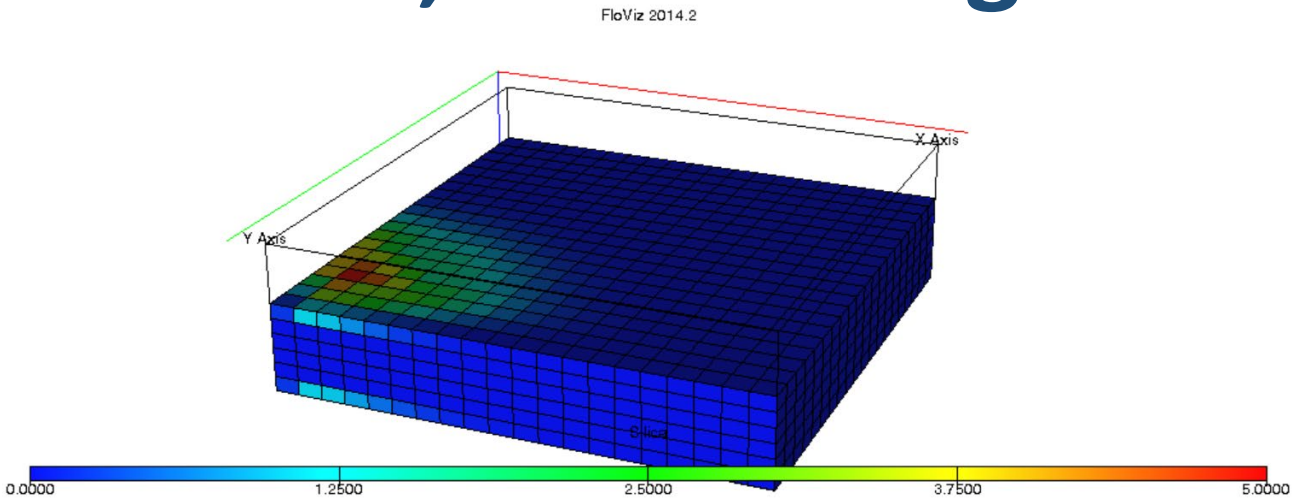


Water injection and production

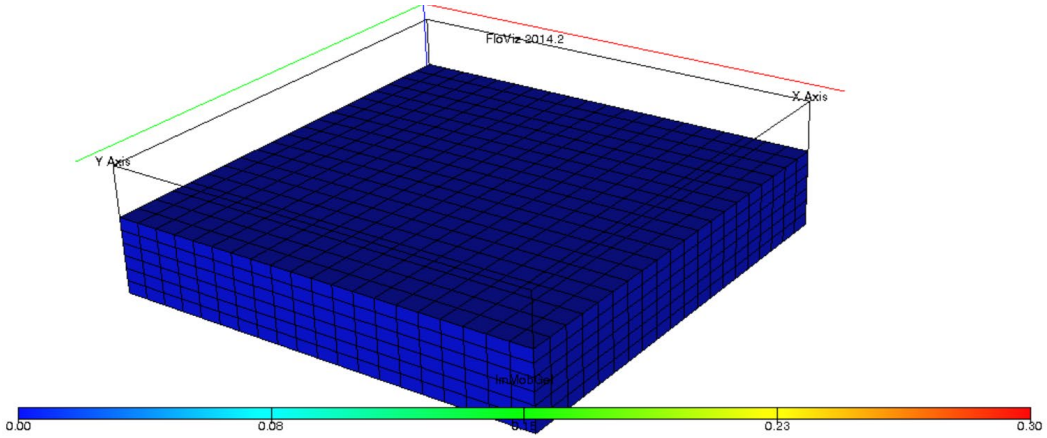




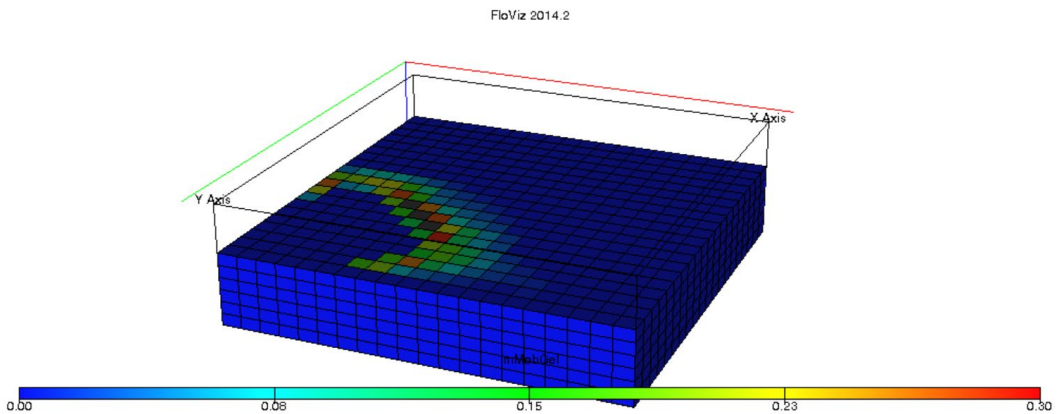
Silica, Immobile gel & SATNUM



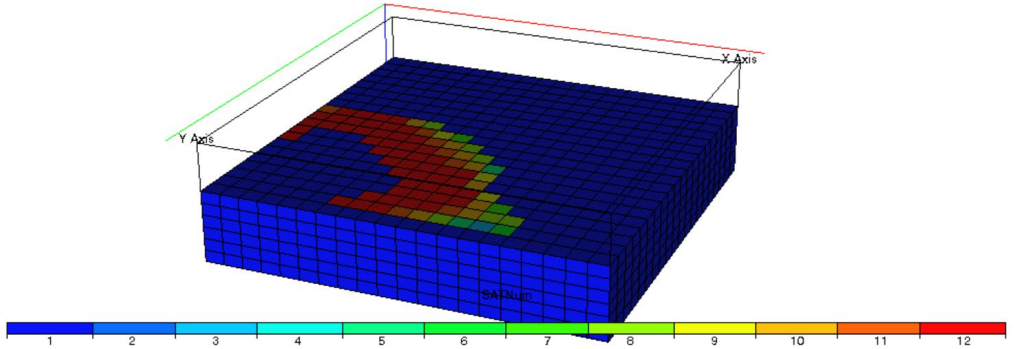
Silica 18.11.20 R33



No Immobile gel 18.11.20 R33

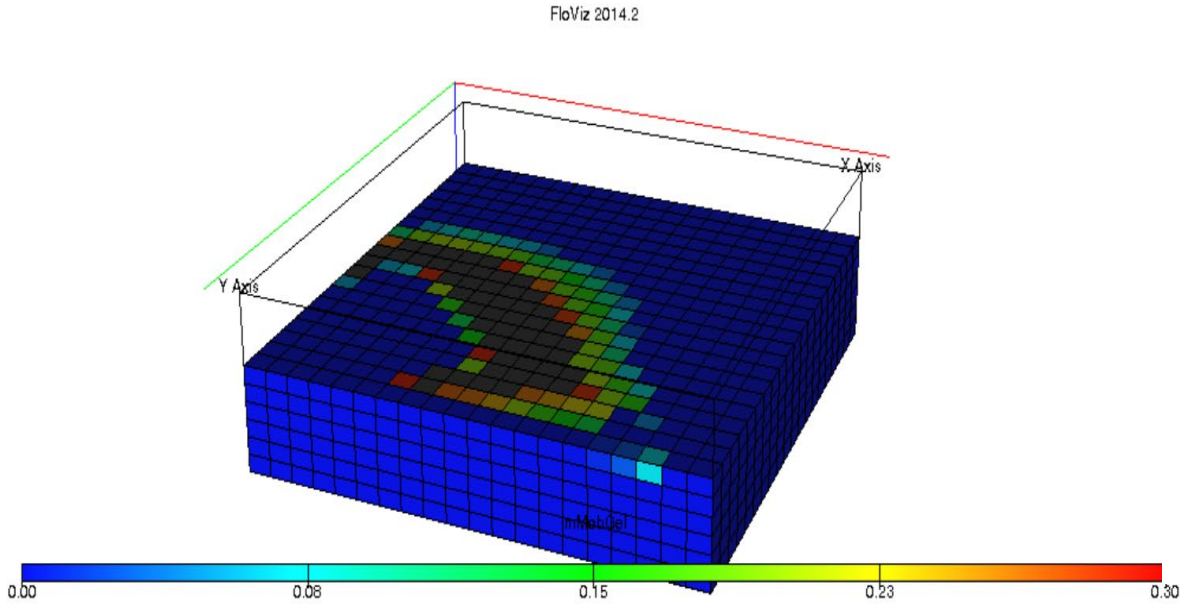


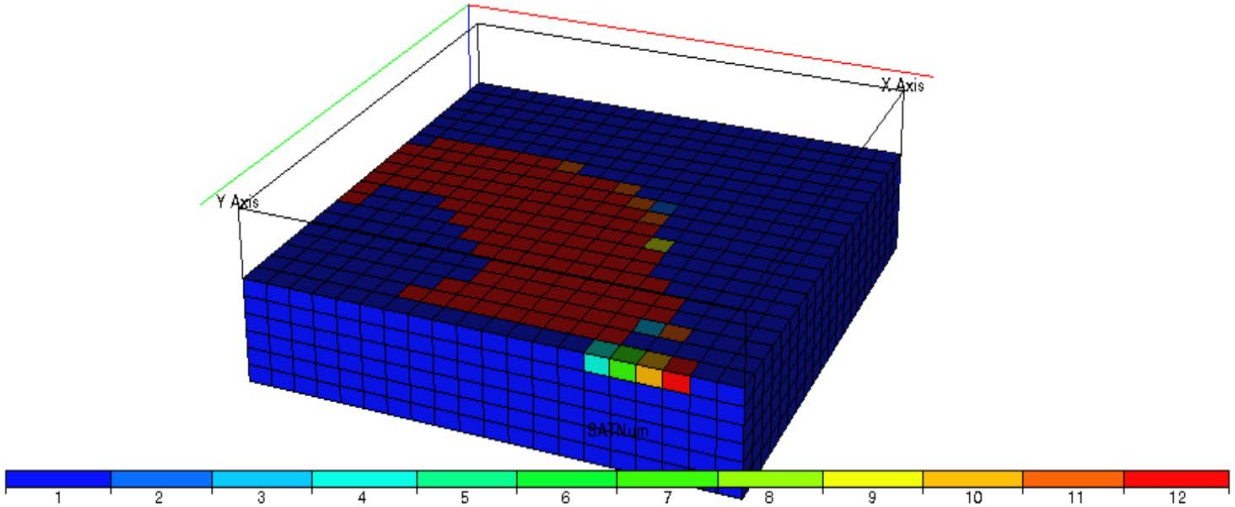
Immobile gel 17.01.21 R37



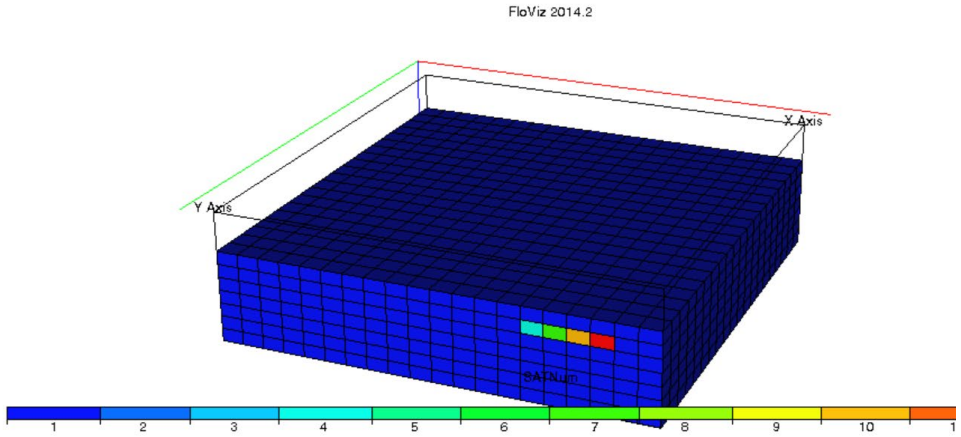
SATNUM 17.01.21 R37

Final – gel and SATNUM

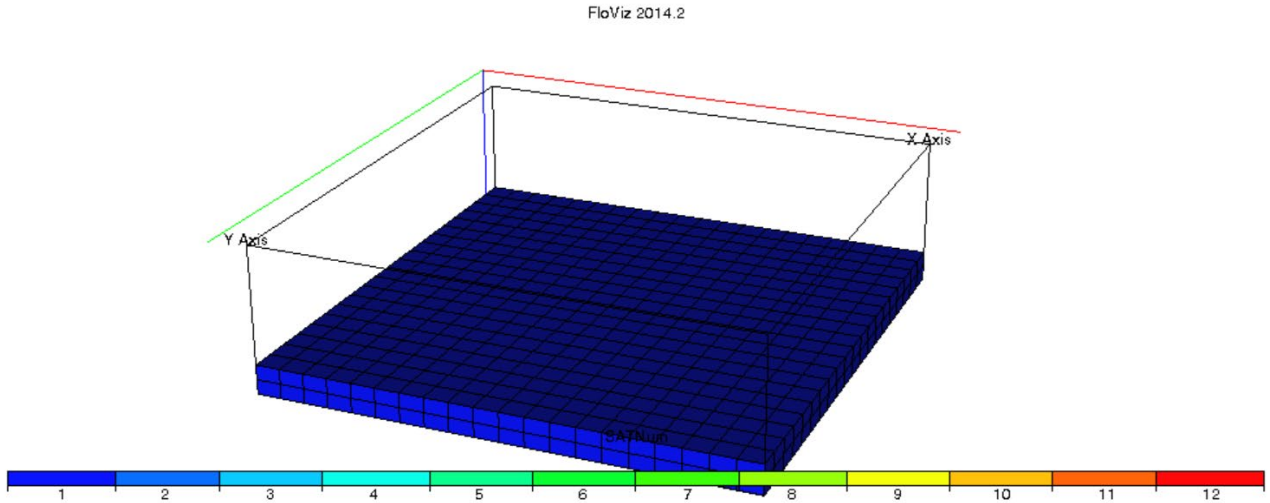




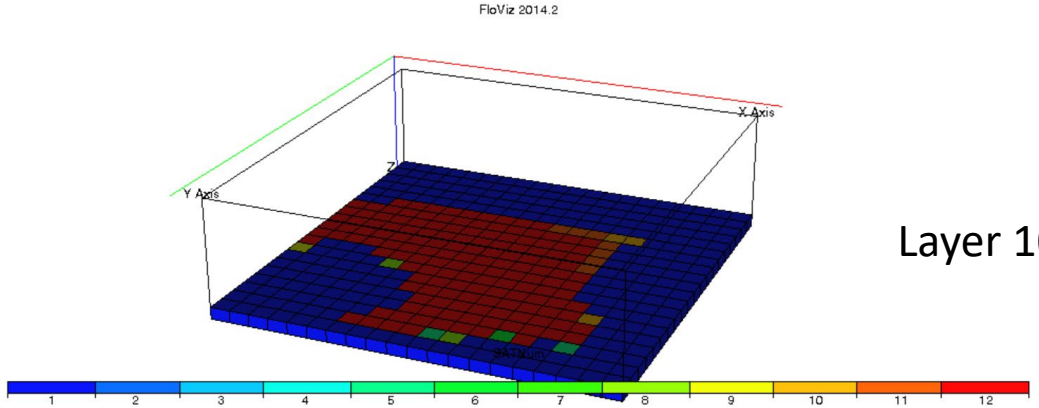
No gel in low permeability layers



Layer 4-10

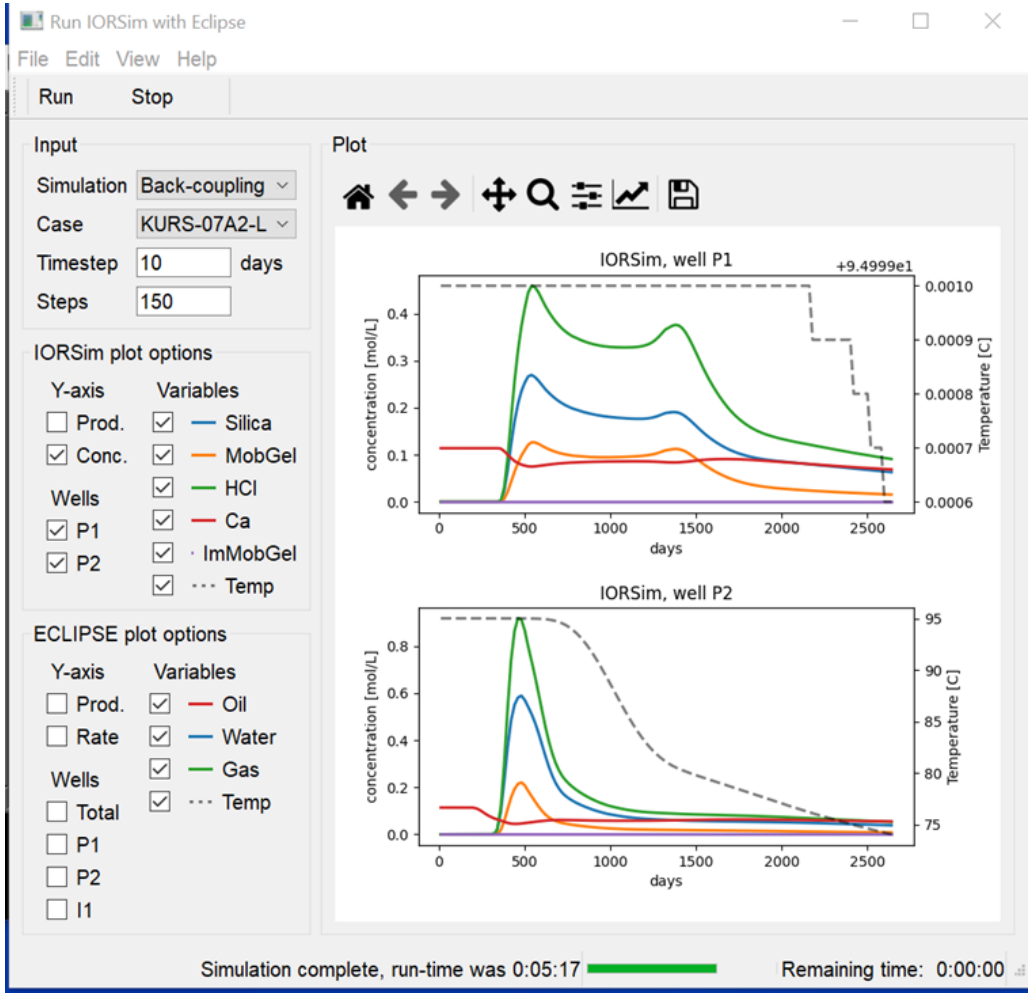


Layer 9-10



Layer 10

IORSim backward GUI



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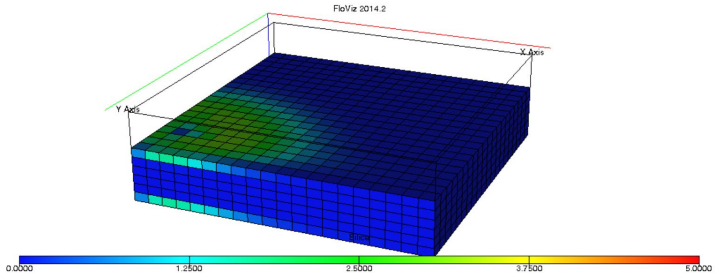
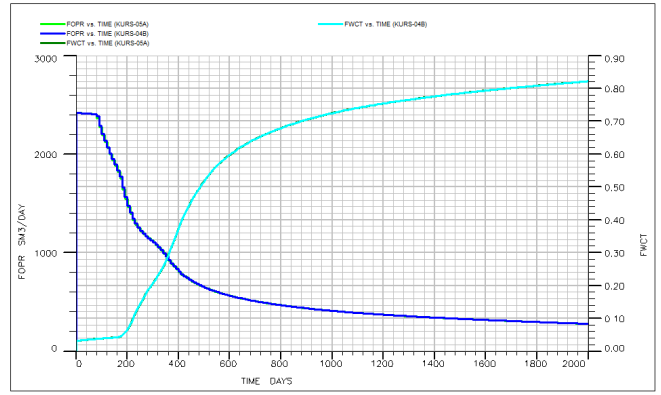
Temperature effect

```
borreja@pc5993 ~/IORSim/python/test
$ diff KURS-05A.trcinp KURS-04A.trcinp
26c26
<      10      20
---
>      5       20
86,87c86,87
<    500 5 0 5.0 0. 0 20
<    530 0 0 0 0.04089 0 20
---
>    200 5 0 5.0 0. 0 20
>    230 0 0 0 0.04089 0 20
```

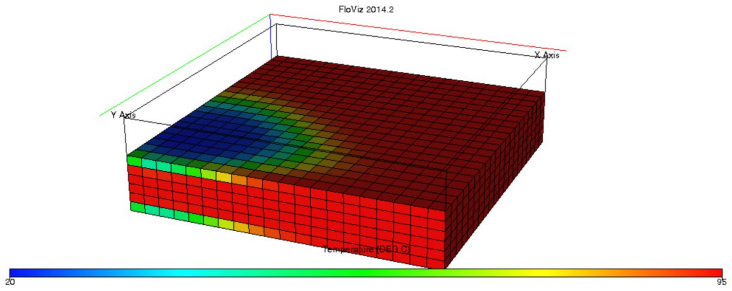
Current 300d



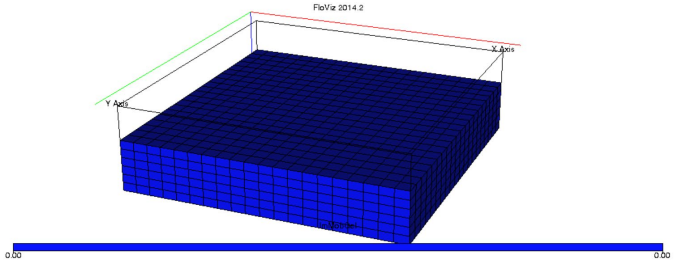
Silica, R55, 26.06.21



Confirming no effect

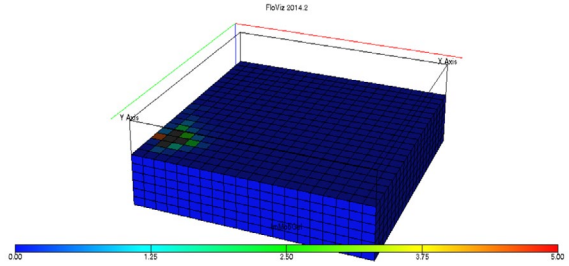


Temperature



Immobile gel (final), R200, 15.06.25

Other: KURS-06A, Heated inj. w.



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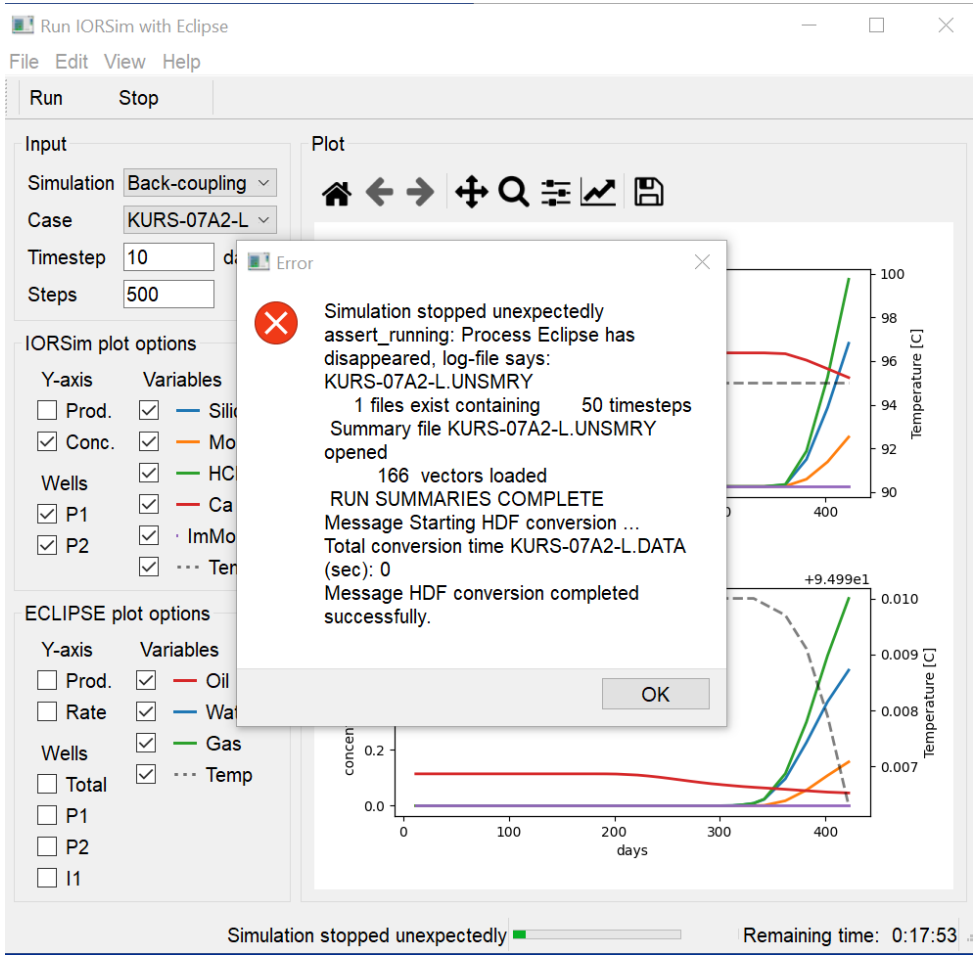
Summary

- IORSim backward modus couples Eclipse and IORSim dynamically.
- Communication takes place through update of SATNUM (relperm tables)
- Technical (simulation) stability has improved significantly
- Very nice GUI created
- Work ongoing for handling well schedule (no problem in Forward)

But sometimes this happens



IORSim

Adding IOR effects to field scale simulations by coupling to the host simulator Eclipse

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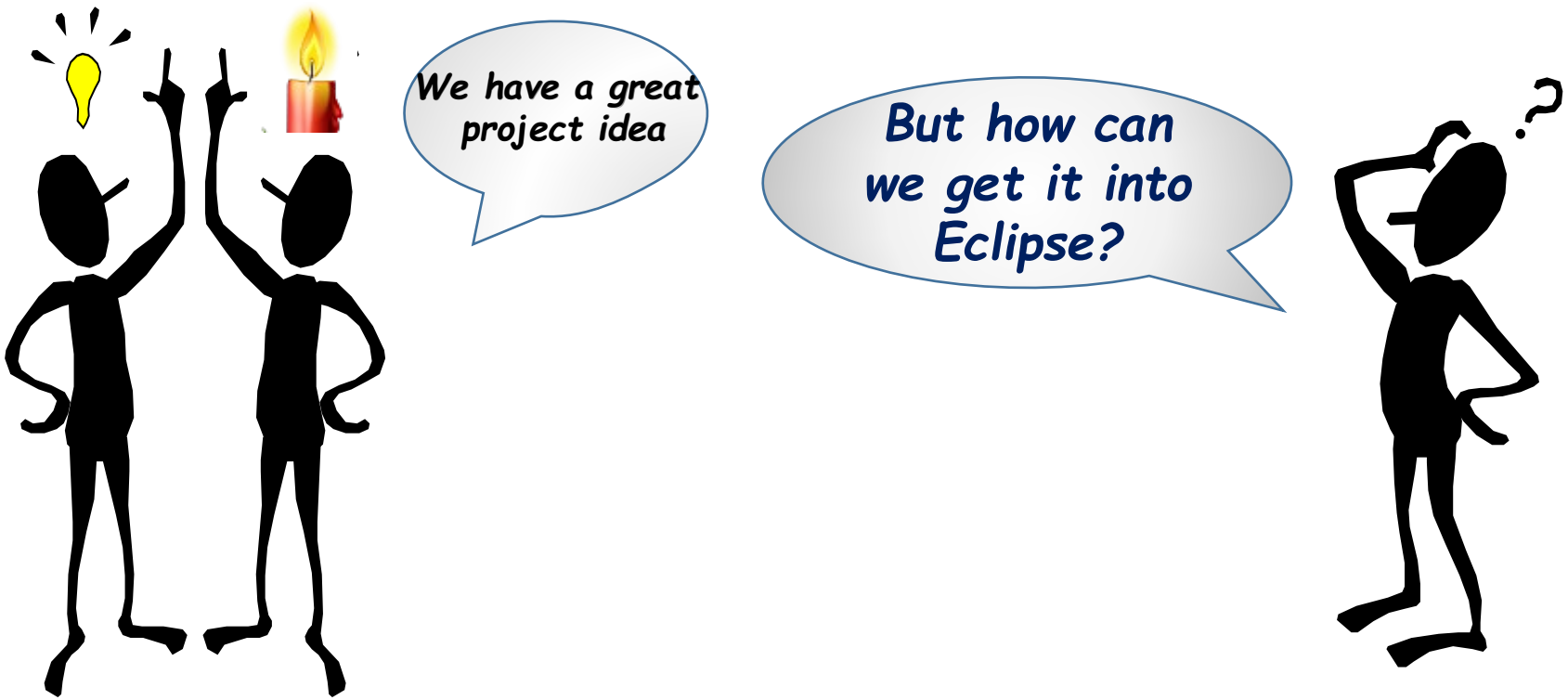
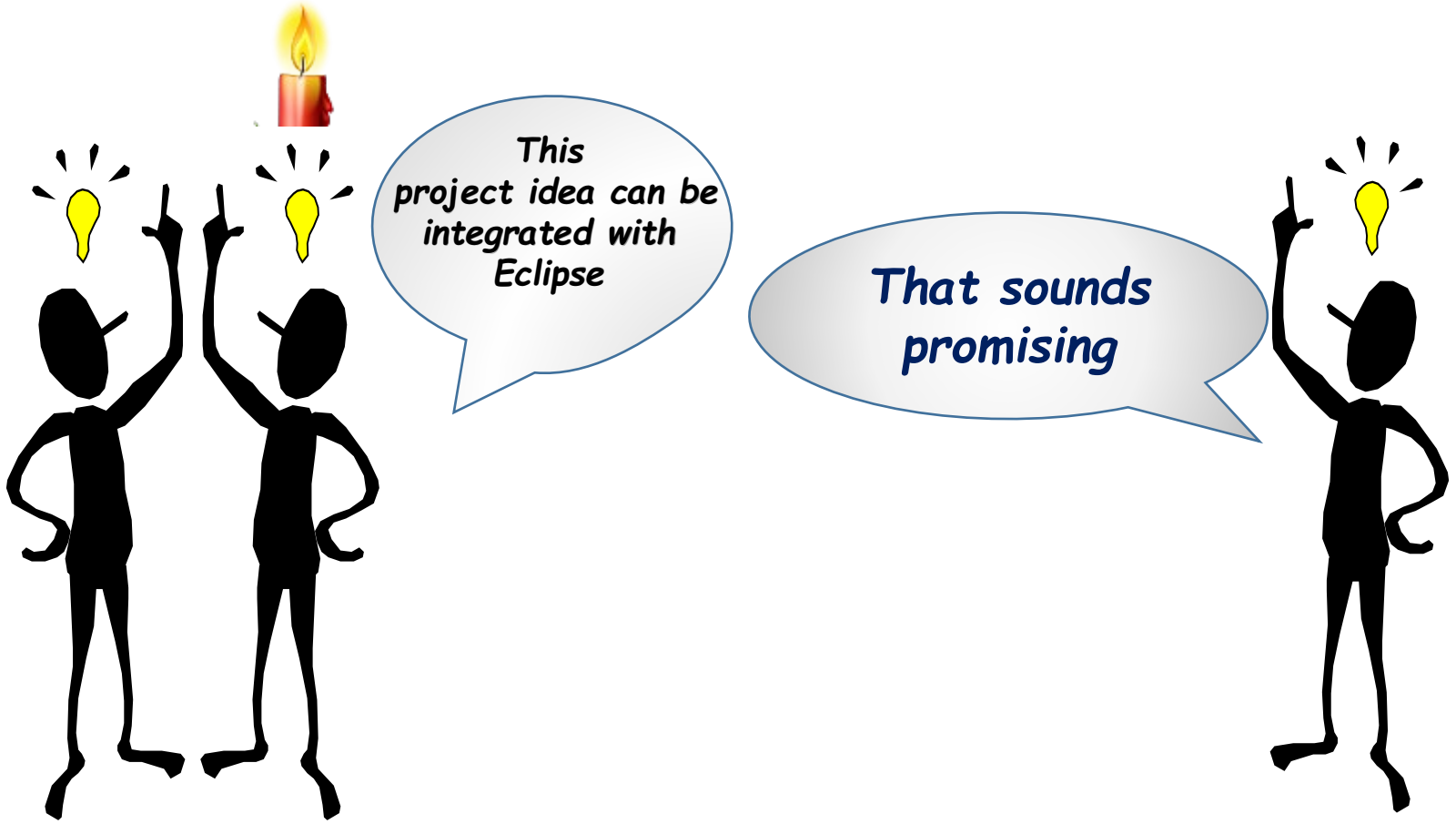
Our traditional experience in proposing projects



Our approach now – IORSim



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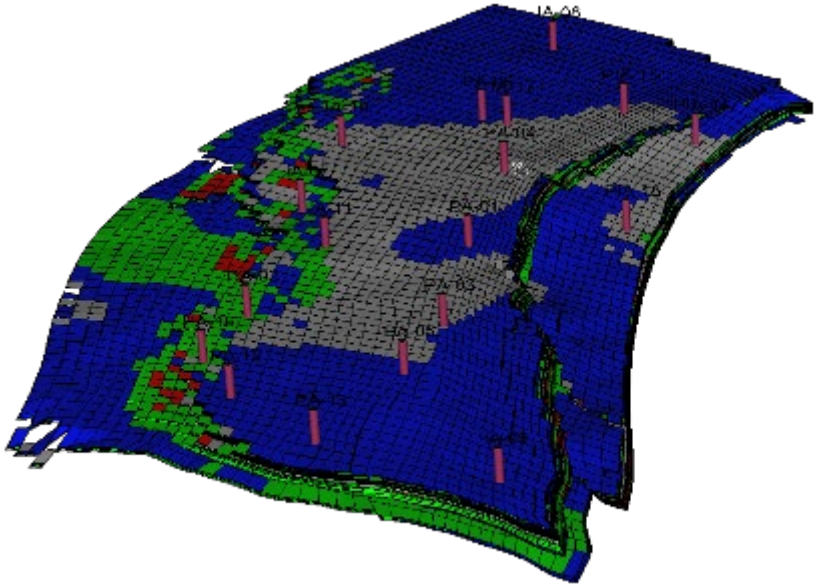
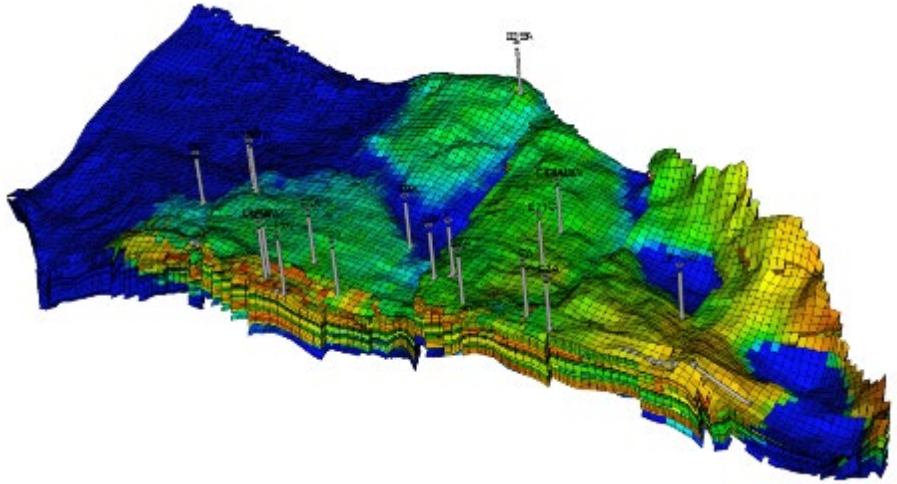
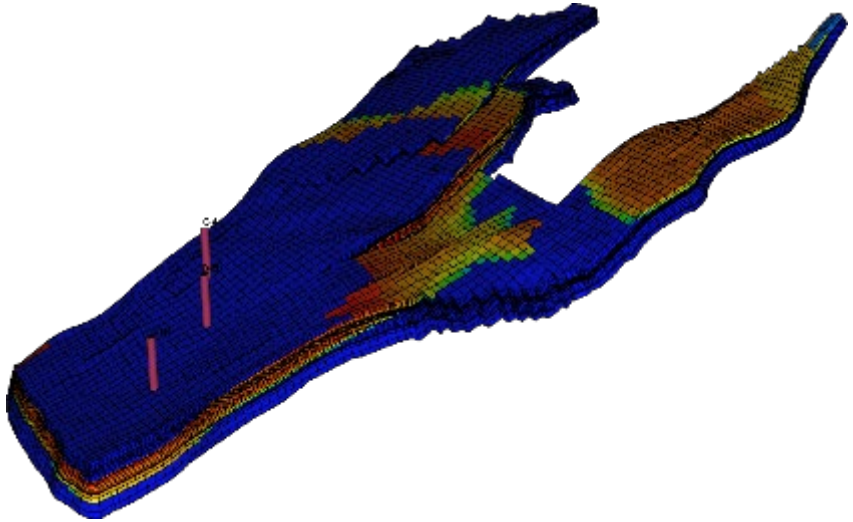
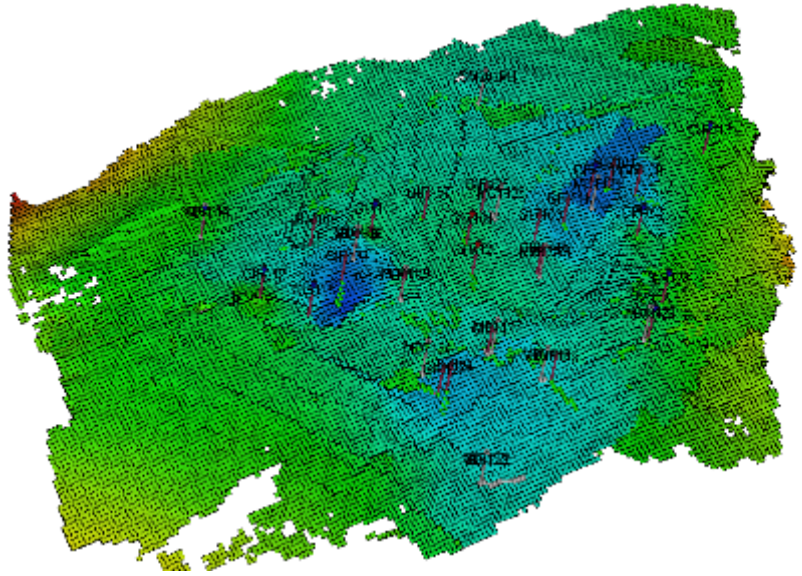
IORSim – An efficient IOR simulation software tool









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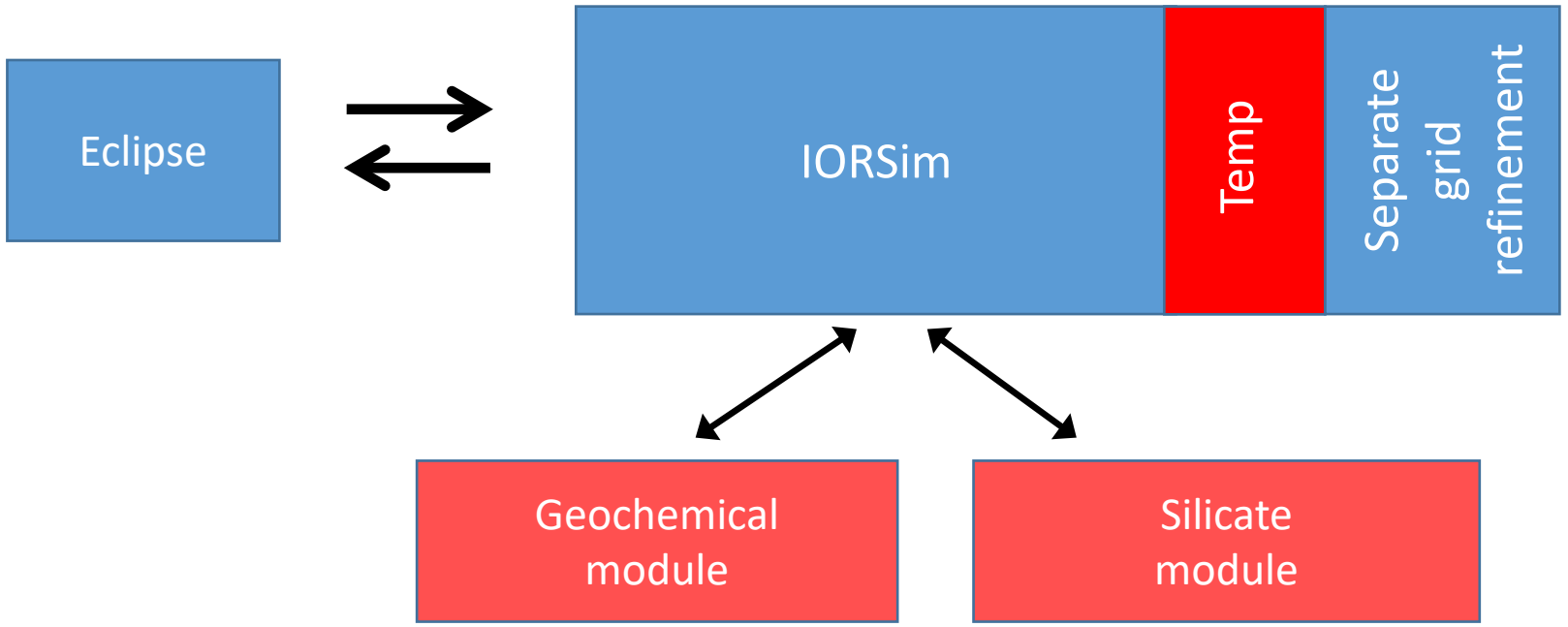
IORSim features

- Geochemical module
- Silicate module
- Chemical species partitioning between the water, oil and gas phase
- The tool allows for taking an existing Eclipse field model, adding:
  - Changes in the water chemistry, low salinity and “smart water”
  - Changes in production due to smart water addition
- The tool may be coupled to other simulators than Eclipse
- IORSim simulates on a separate grid relative to the host simulator (separate grid refinement)

Eclipse model – IORSim two way coupling

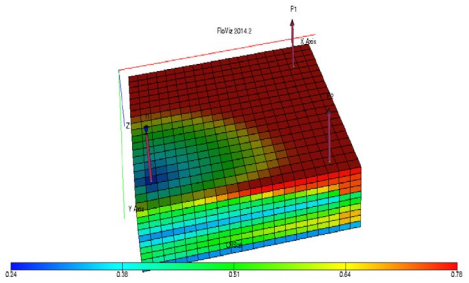


Partitioning species

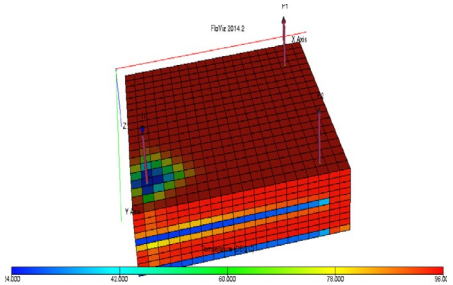
Sequential solution method in IORSim

- Sequential method is needed since species transport is combined with geochemistry
- Sequential method for water species
- Sequential method for temperature calculation
- Sequential method for partitioning species

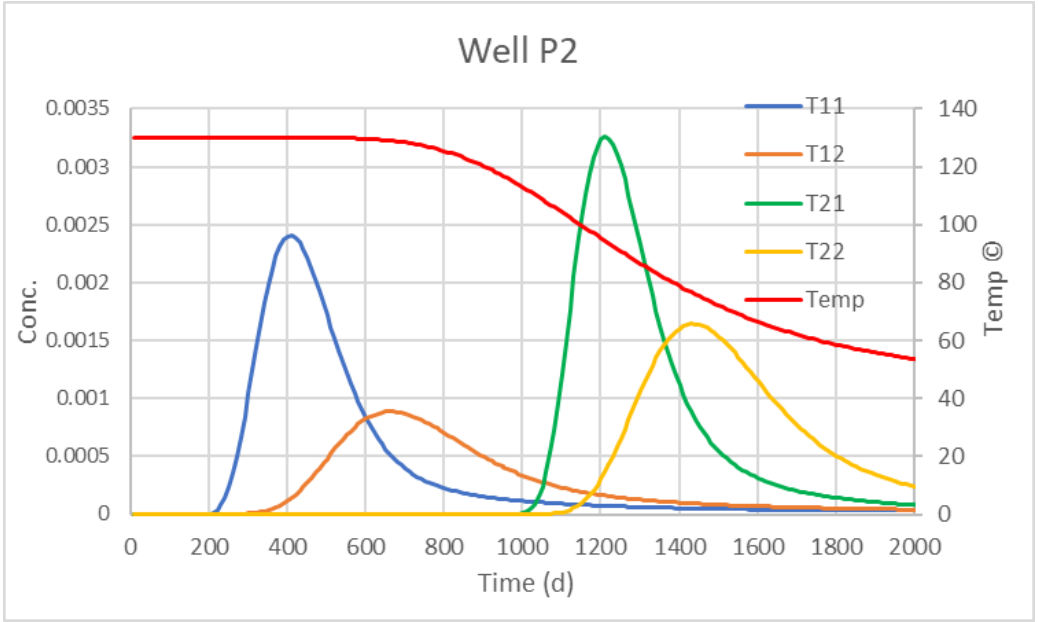
Tracer simulations in “KURS-04B”



Oil sat.

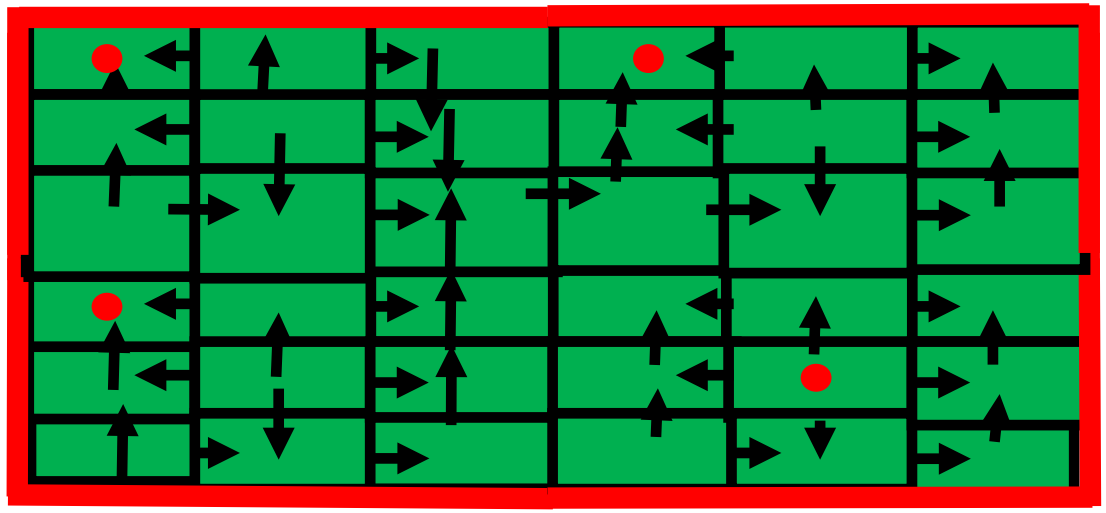


Temperature



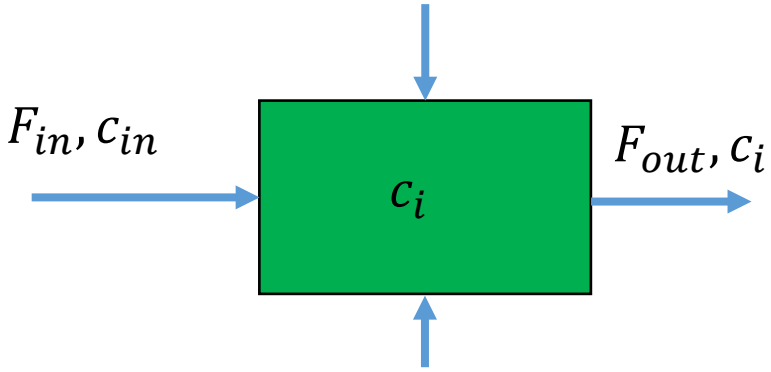
		Tm inj. (d)	Peak (d)	D_t (d)	Peak_Dt
T11	Ideal	100	402	302	
T12	K=2	100	662	562	260
T21	Ideal	950	1212	262	
T22	K=2	950	1432	482	220

Why can't we solve it in the «normal» way ?



- Difficult to converge
- Long computing time

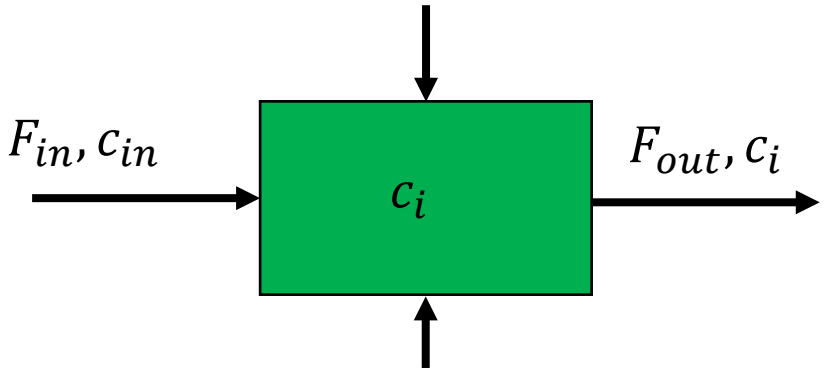
To include geochemistry, we need to «localize» the problem



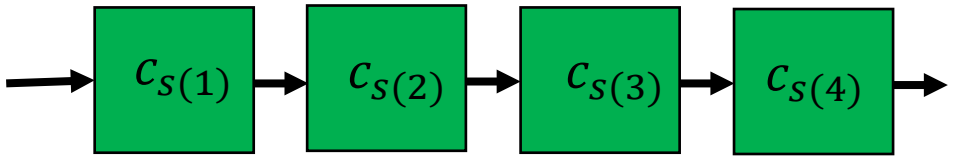
How can we make c_{in} known in advance ?

Answer: Solve it first

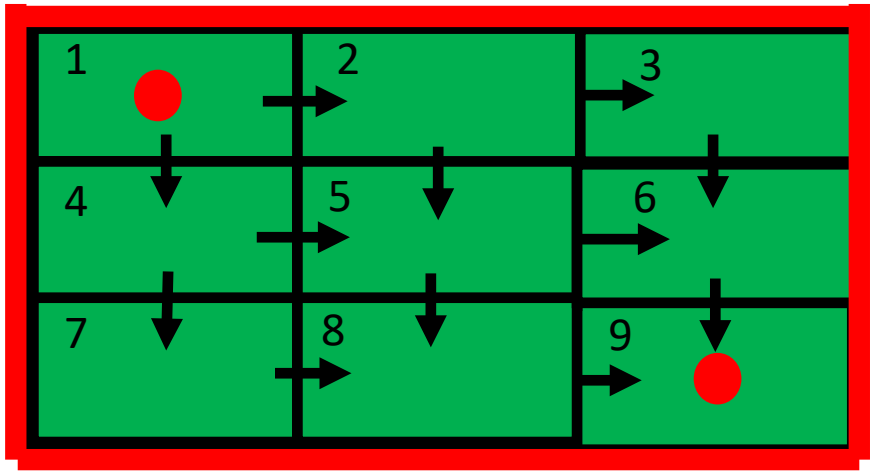
We need to make the problem «1D»



Implicit integration



How can we make the problem «1D»:

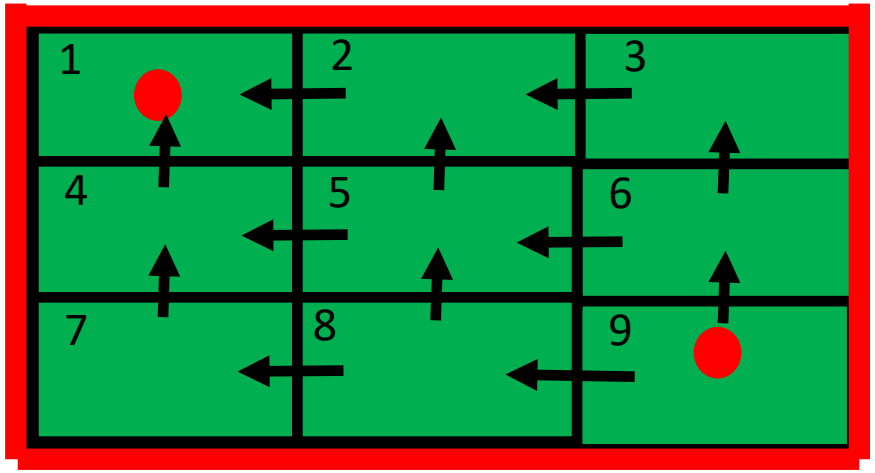


Block sequences that will work:

1, 2, 3, 4, 5, 6, 7, 8, 9

1, 4, 7, 2, 5, 8, 3, 6, 9

Turning the flows:

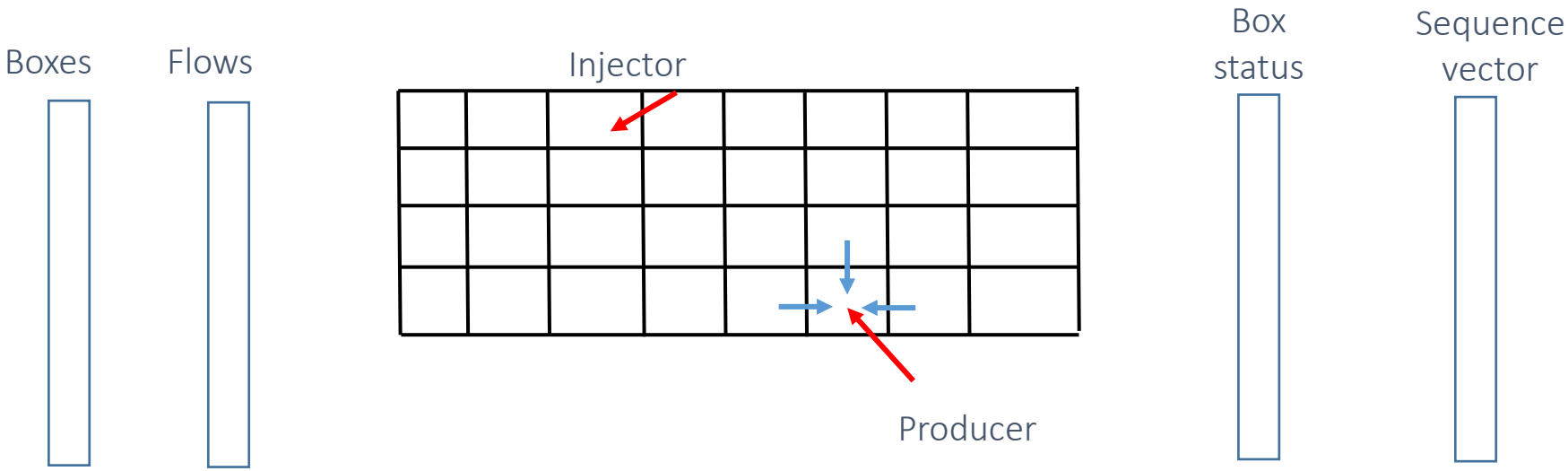


Block sequences that will work:

9, 8, 7, 6, 5, 4, 3, 2, 1

9, 6, 3, 8, 5, 2, 7, 4, 1

The sequential method for water species in IORSim:

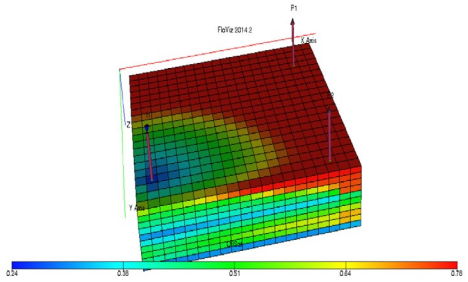


IncludeBox routine

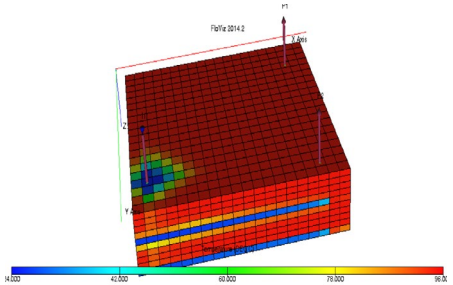
Checks for alle inflows into a box, if the upstream box is included.

If not: Call IncludeBox for this box, and include box in sequence vector

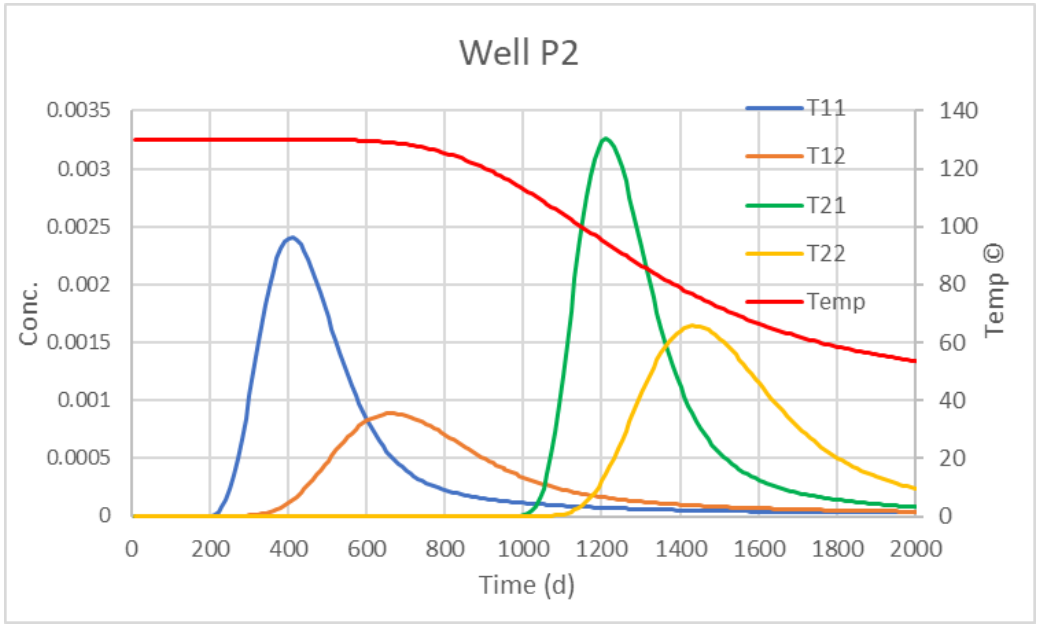
Tracer simulations in “KURS-04B”



Oil sat.



Temperature

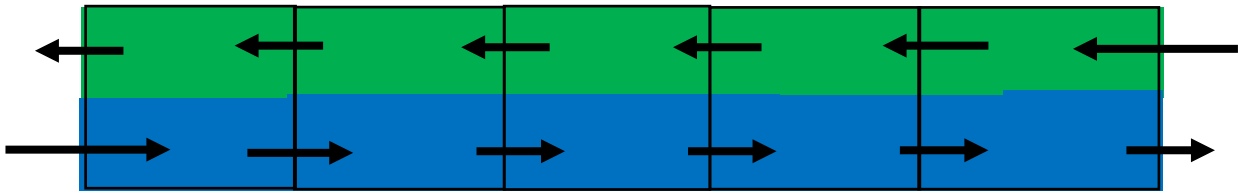


		Tm inj. (d)	Peak (d)	D_t (d)	Peak_Dt
T11	Ideal	100	402	302	
T12	K=2	100	662	562	260
T21	Ideal	950	1212	262	
T22	K=2	950	1432	482	220

Partitioning species

- The sequential method for water species has been extended to handle species which exist in all three phases (water, oil, gas)
- Species are assumed to be in equilibrium between the phases
- The concentration in each phase is calculated as
  $Cw = Kw*C$, $Co = Ko*C$, $Cg = Kg*C$
- Concentration C is calculated for all grid blocks at each time step
- Kw, Ko, Kg may be dependent on P, T and composition
- The partitioning species option in IORSim may be useful for instance when CO2 is present in water, oil and gas

The sequential method for partitioning species



Strategy:

When Cw*Fw > Cw*K*Fo we use new concentration (implicit) for the water term

When Cw*Fw < Cw*K*Fo we use new concentration (implicit) for the oil term

Stability analysis

- Assuming use of the implicit (new) concentration in the water transport term, and explicit (old) concentration in the opposite direction oil term

  (Semi-implicit method)

- Børre Antonsen performed stabiliy analysis and showed the following inequality:

$$\Delta t \frac{Fw - K * Fo}{(s + (1 - s) * K)} \geq -V$$

  where Fw is water rate, Fo is oil rate, K is species partitioning coefficient between water and oil ,

  Co = K*Cw

- This shows that the method is always stable when Fw > K*Fo

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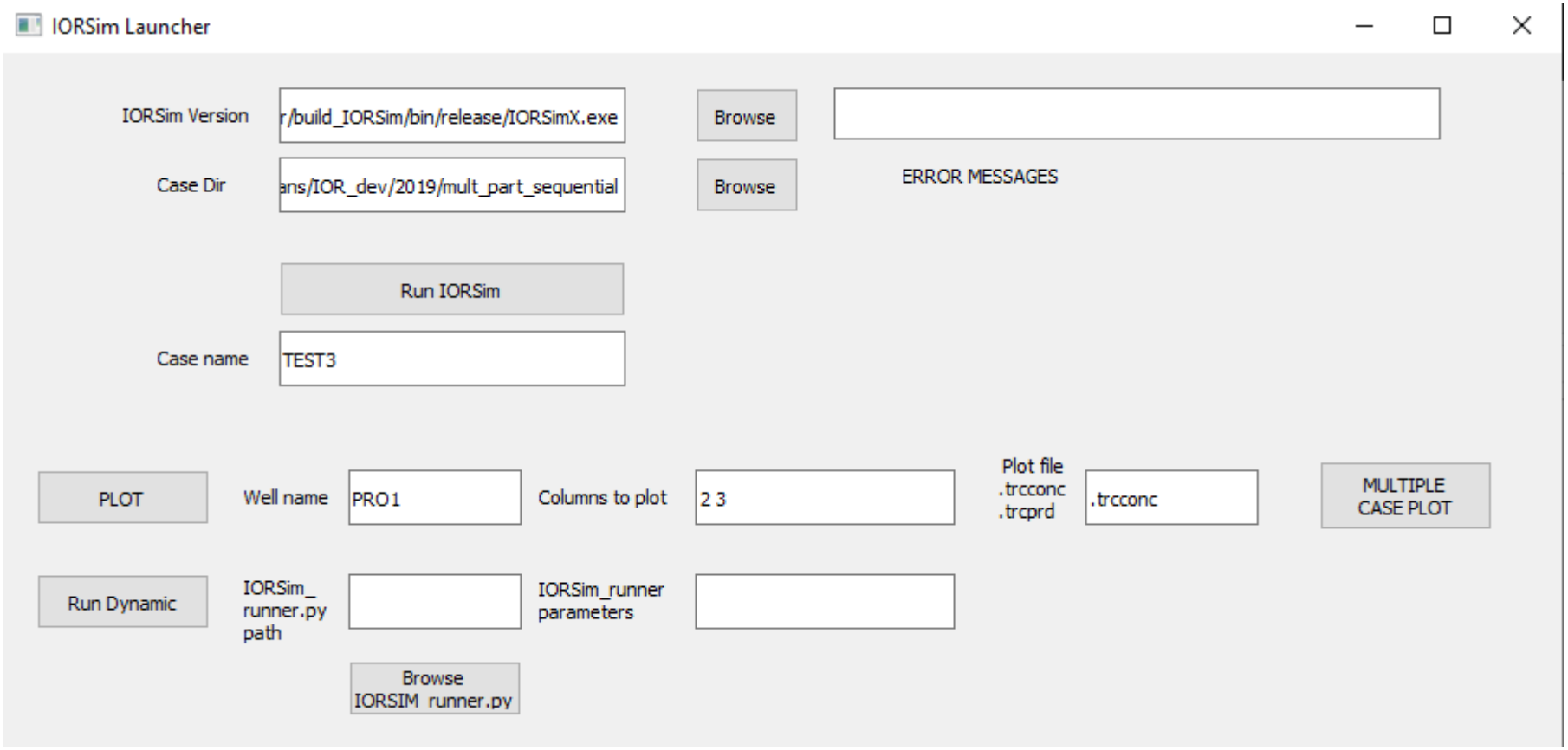
IORSim_launcher



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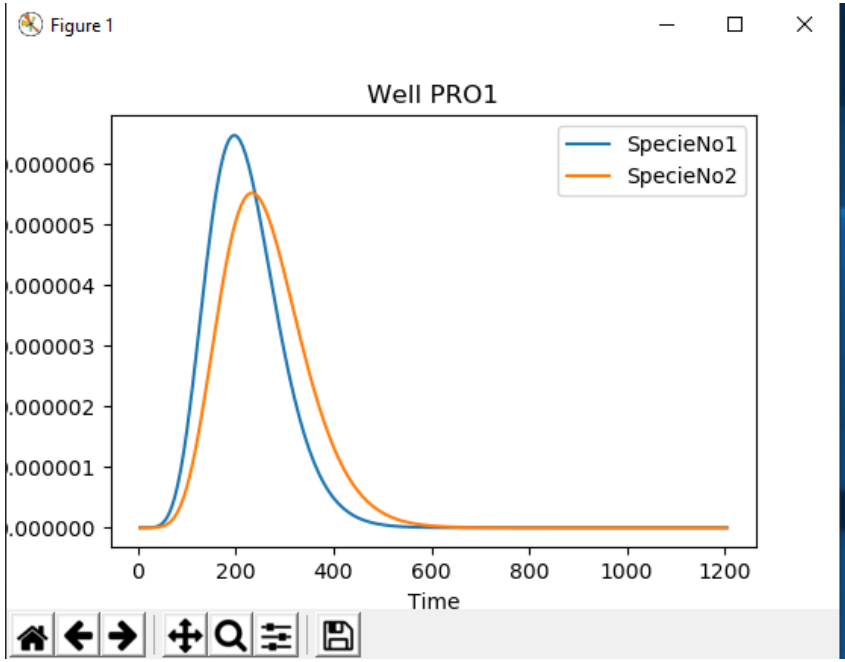

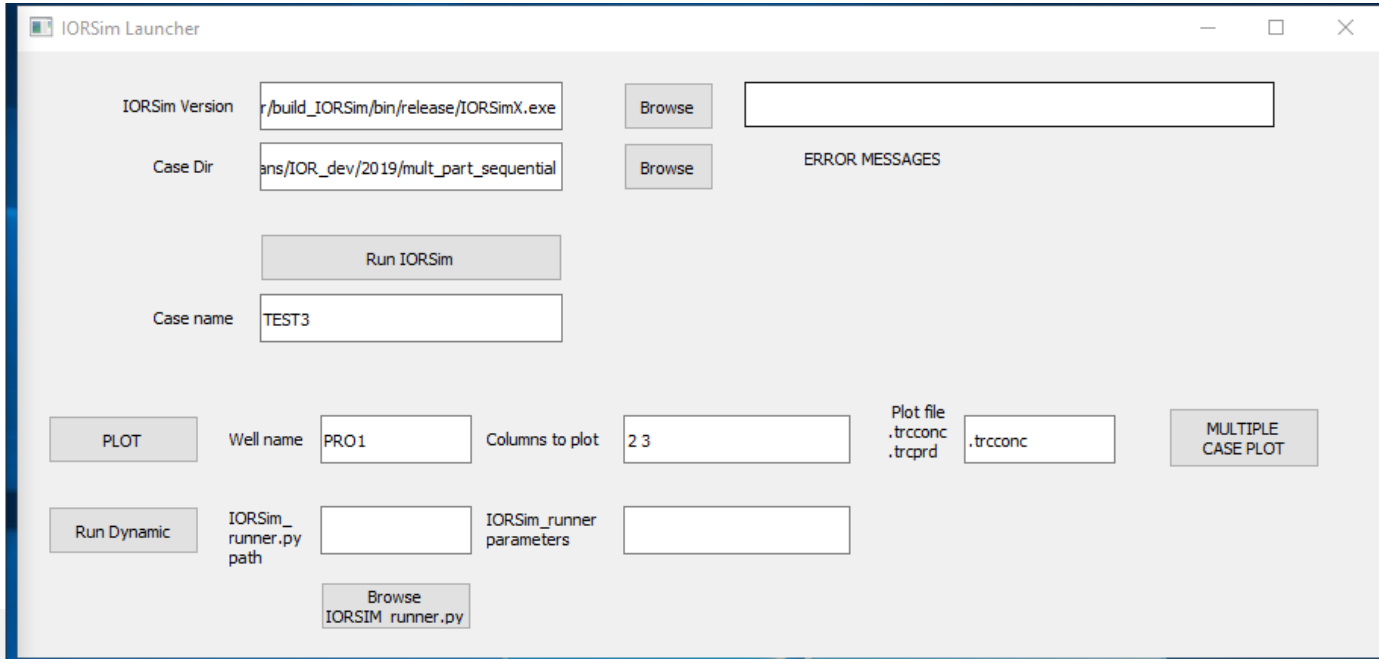

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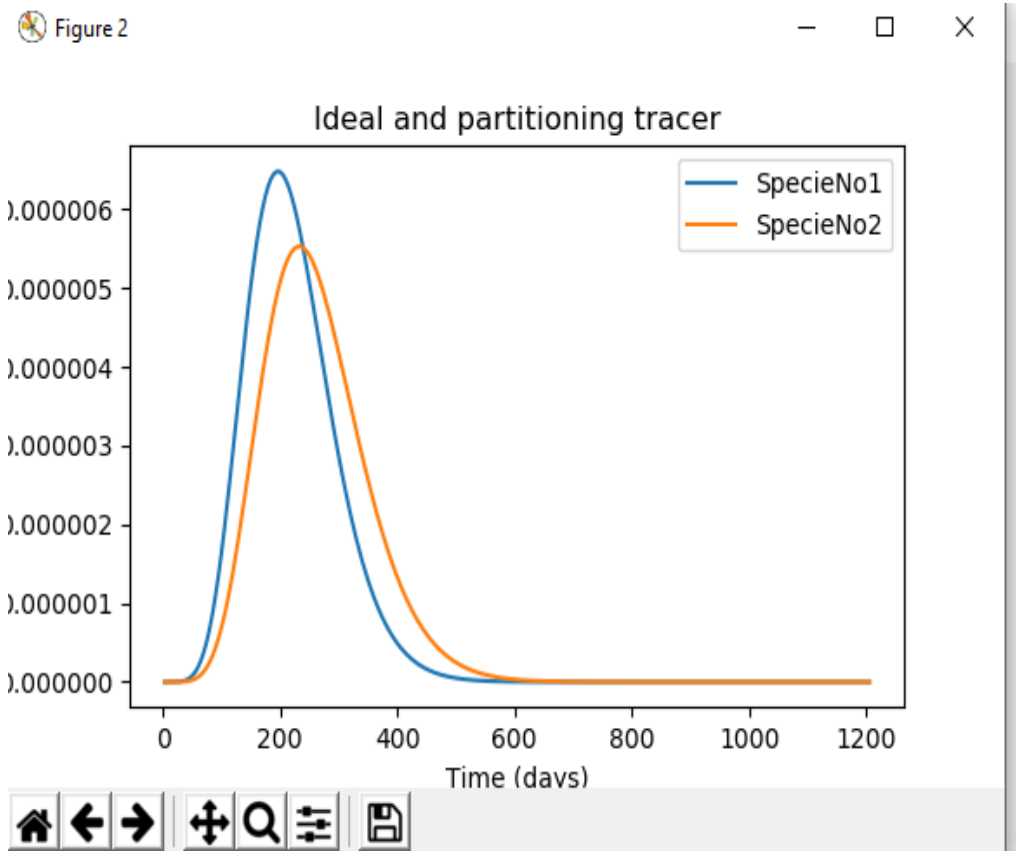
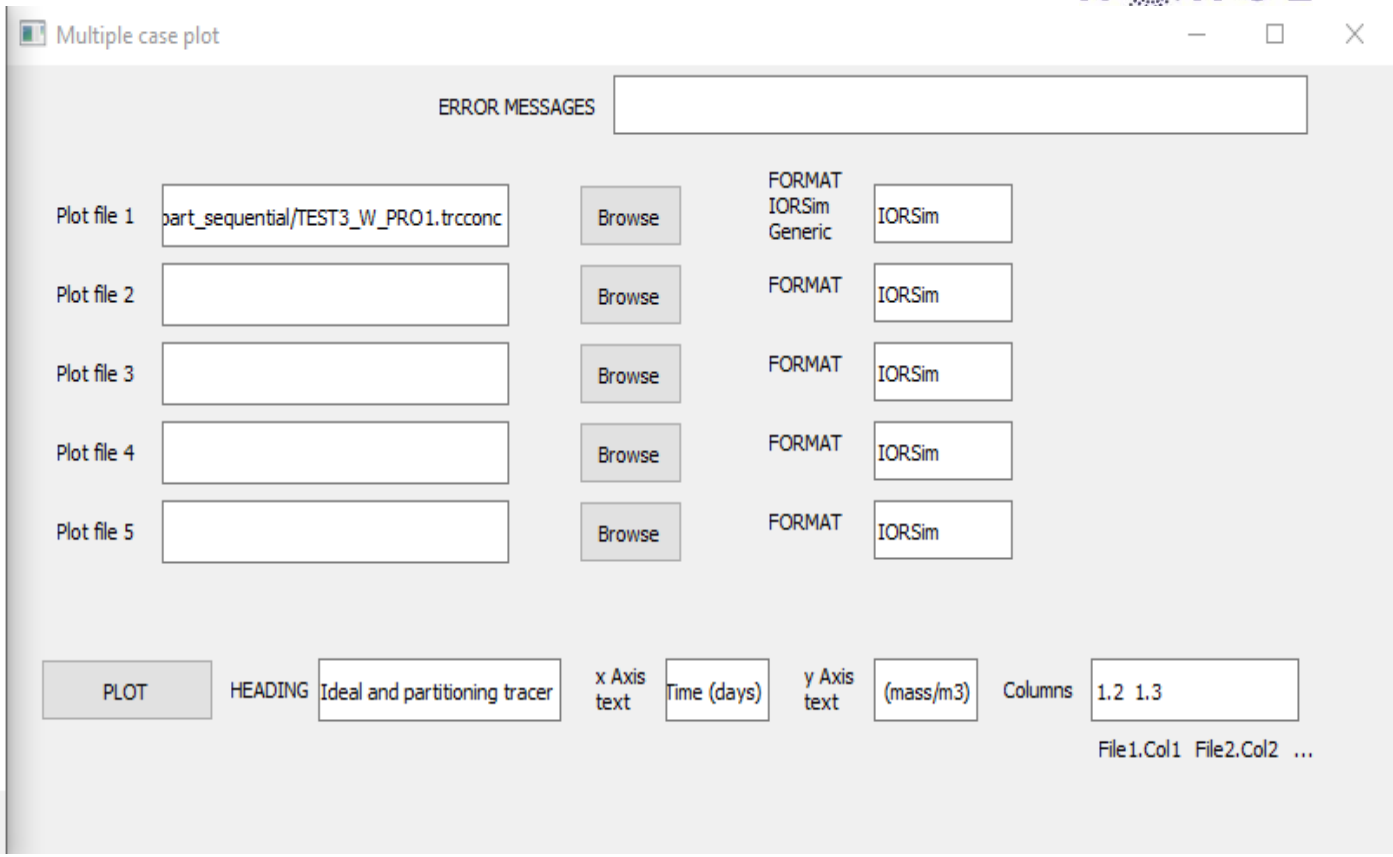
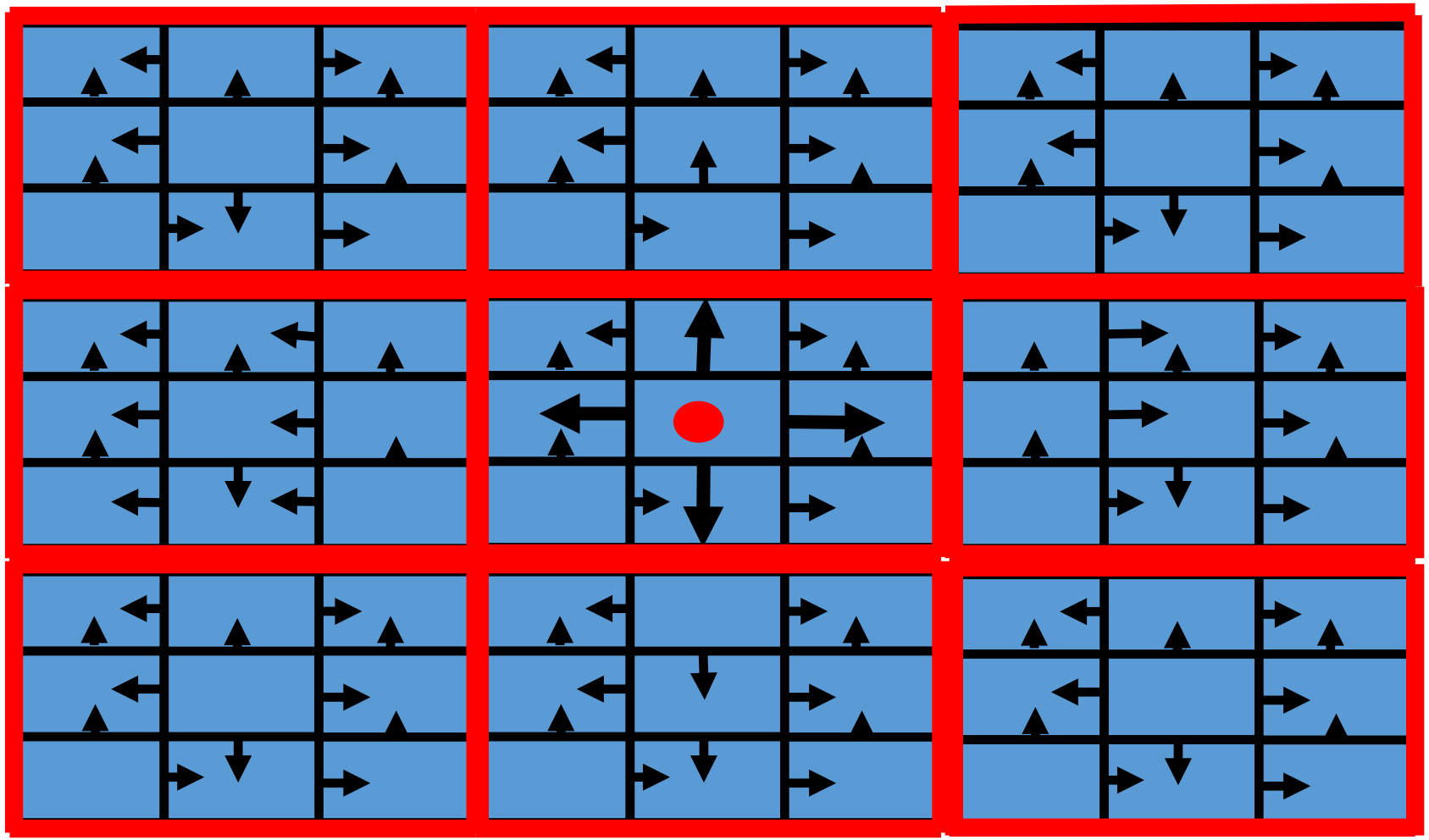




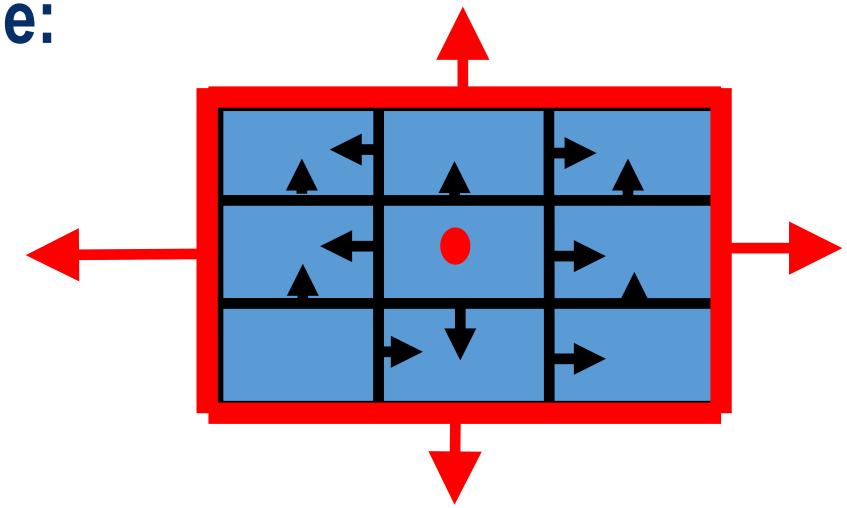
Grid refinement for species grid



Mass conservation of one phase:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underline{v}) = 0$$

$$\rho = \rho(t): \qquad \frac{1}{\rho}\frac{\partial \rho}{\partial t} + \nabla \cdot \underline{v} = 0$$



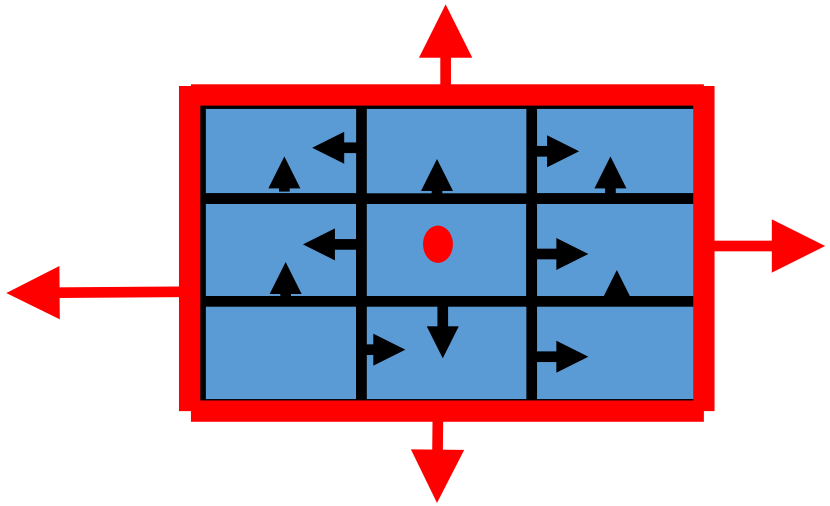
Inclusion of compressibility:

$$V\frac{\partial \rho}{\partial t} = \frac{dM}{dt} = \rho(Q - \sum_i Q_i) \quad \longleftrightarrow \quad \frac{1}{\rho}\frac{\partial \rho}{\partial t} = \frac{Q - \sum_i Q_i}{V}$$

Final pressure equation to be solved:

$$-\nabla \cdot (\underline{v}) = \nabla \cdot (K \nabla P) = \frac{Q - \sum_i Q_i}{V}$$

Pressure equation to be solved for each phase:



Transmissibility in x-direction: Tx

Transmissibility in y-direction: Ty

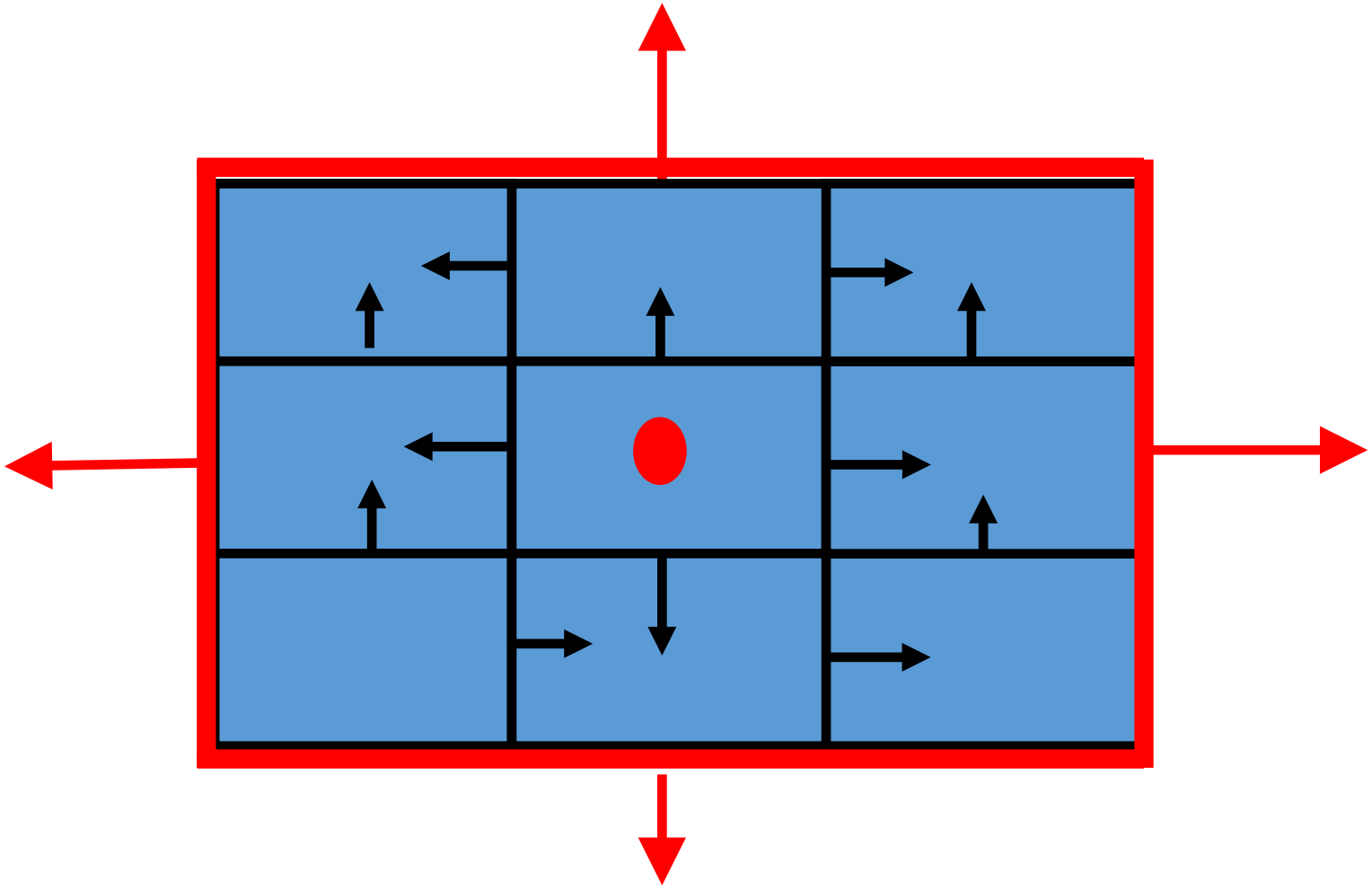
$$T_x\left(P_{i,j,k} - P_{i+1,j,k}\right) + T_y\left(P_{i,j,k} - P_{i,j+1,k}\right) + T_z\left(P_{i,j,k} - P_{i,j,k+1}\right) +$$
$$T_x\left(P_{i,j,k} - P_{i-1,j,k}\right) + T_y\left(P_{i,j,k} - P_{i,j-1,k}\right) + T_z\left(P_{i,j,k} - P_{i,j,k-1}\right)$$
$$= \frac{V_{i,j,k}}{V}\left(\sum_i Q_i - Q_{well}\right) + Q_{well}$$

Phase rate in each direction: $Q_x = T_x\left(P_{i,j,k} - P_{i+1,j,k}\right)$

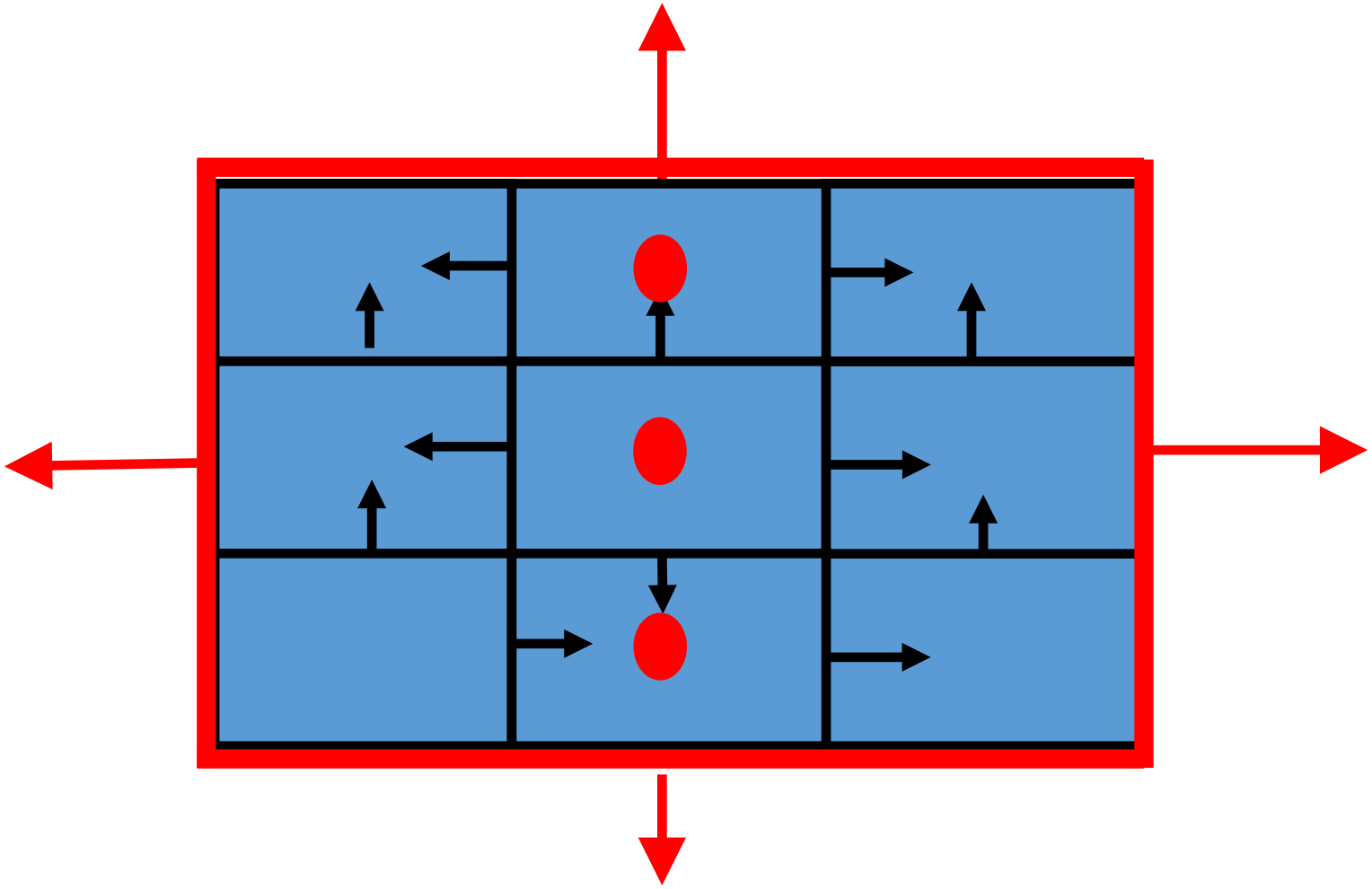
$$Q_y = T_y\left(P_{i,j,k} - P_{i+1,j,k}\right)$$

$$Q_z = T_z\left(P_{i,j,k} - P_{i+1,j,k}\right)$$

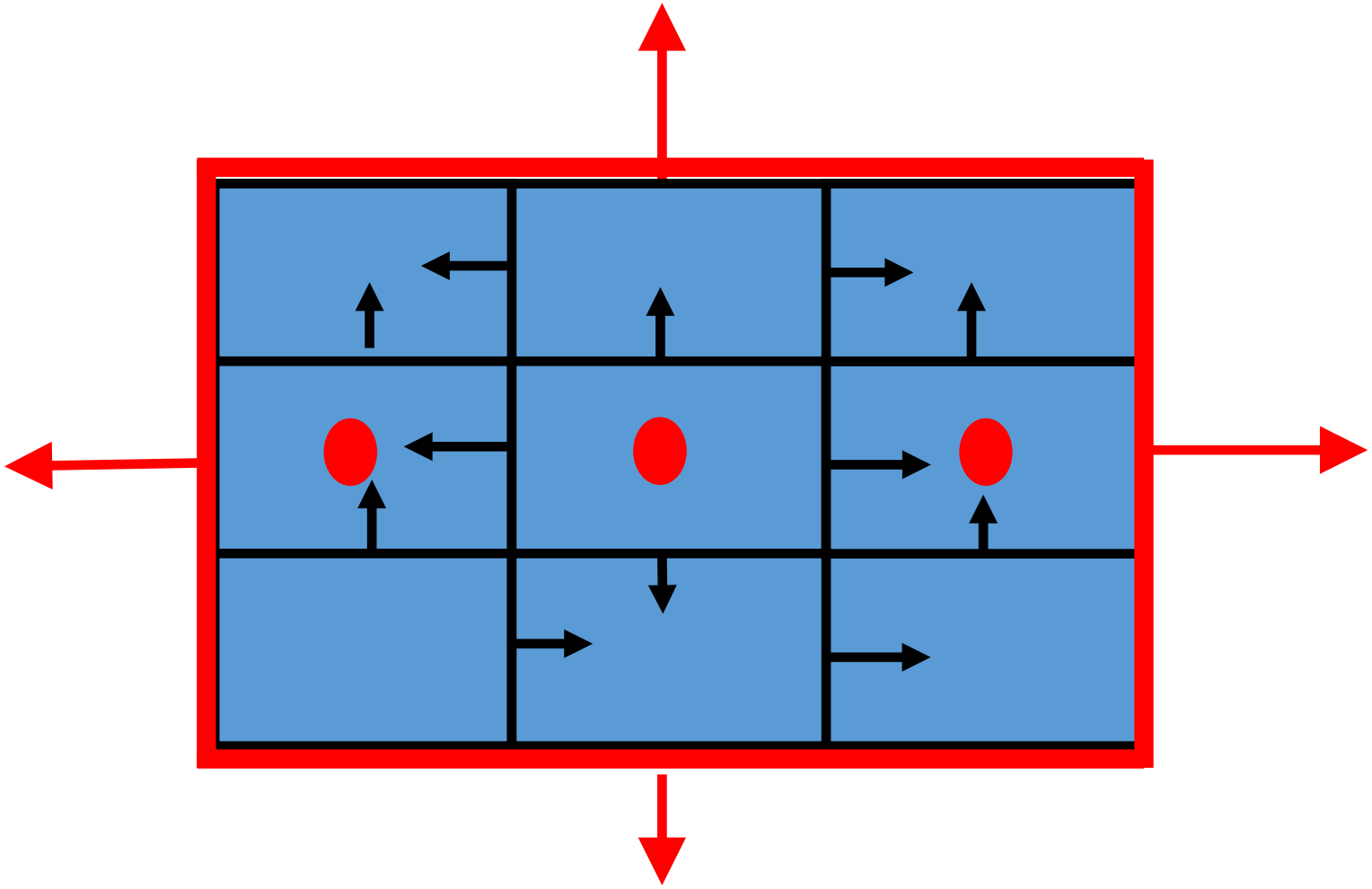
Vertical well, areal view:

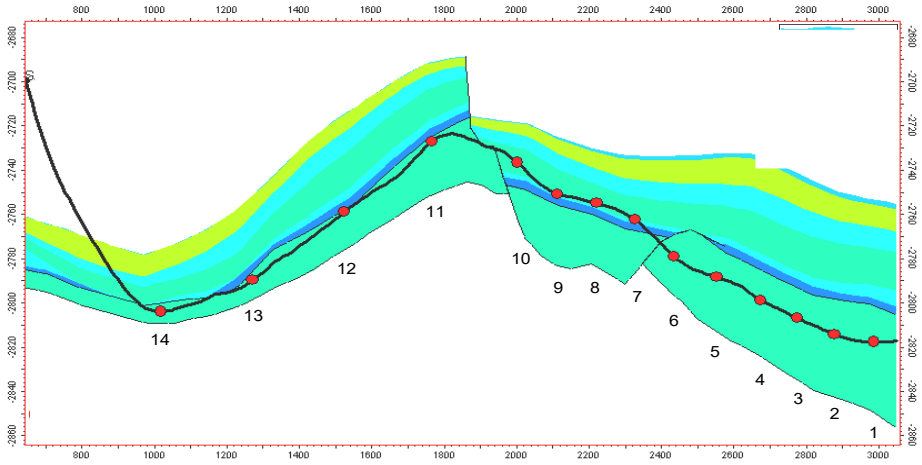


Vertical well, cross-sectional view:



Horizontal well:

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