TNO usage of OPM Flow in geothermal applications

OPM Summit 2026

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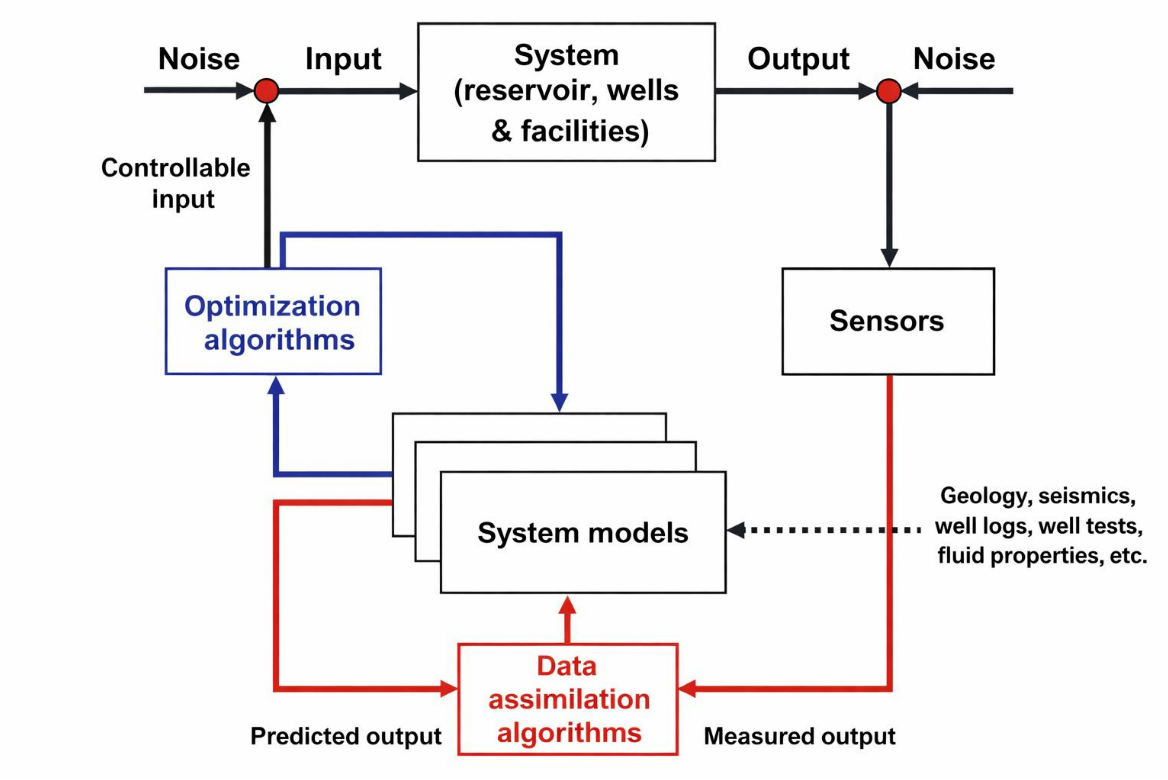
(on behalf of Reservoir Modelling and Optimization team)

OPM OPEN POROUS MEDIA

TNO innovation for life

OPM Flow in closed loop reservoir management

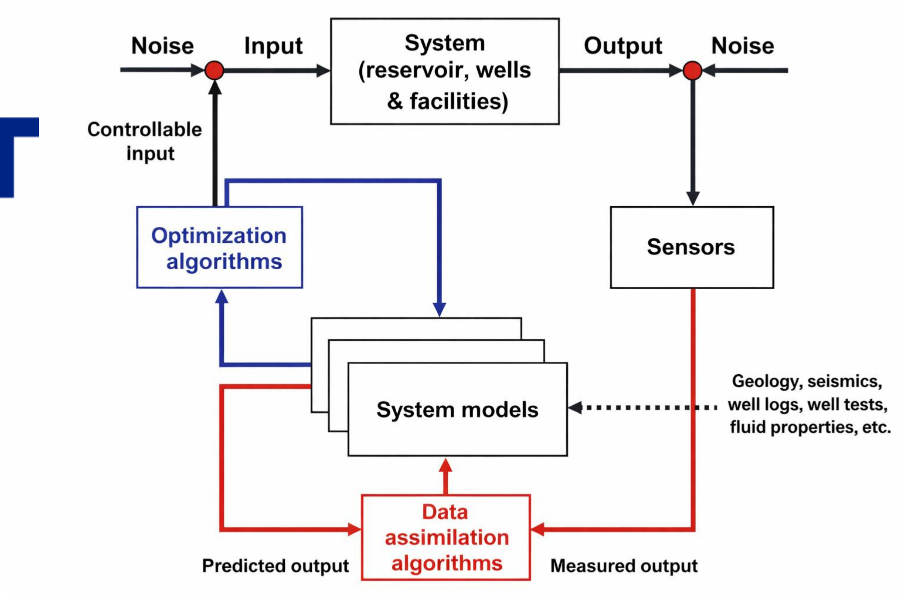
- Reservoir simulations key part of **Closed-Loop Reservoir Management:**
  - Data assimilation.
  - Decision optimization.
  - Proxy modelling.
  - Value of Information.
- Ensemble of models representing uncertainty:
  - **Many reservoir simulations** required.
- **Physics relationships** specific to application.
- **Accuracy and performance** are important. ("An iteration is as fast as the slowest model")
- **Parallel computing** can help significantly. (Simulations run on HPC where Open MPI and CUDA are available, benefit of Open Source)



Open-source ecosystem integration

EVEREST

https://everest.tools



ResInsight

https://resinsight.org/

ert

https://ert.readthedocs.io

python™ Java

OPM OPEN POROUS MEDIA

https://opm-project.org/

Economics

Geomechanics

PyThermoNomics

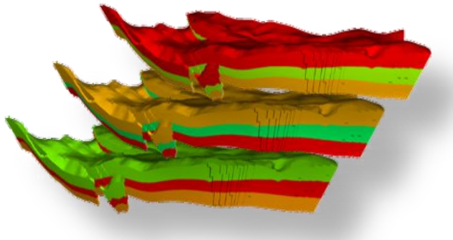
https://github.com/TNO/pythermonomics

Drilling

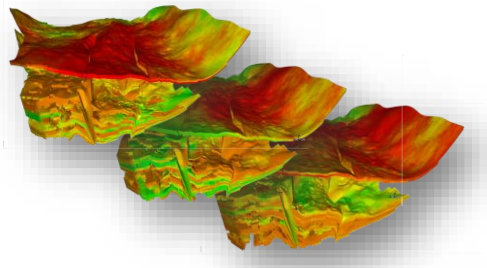
Recent geothermal Projects at TNO

Case studies

- **TKI GE** Middenmeer: Plan to drill 6 wells (3 doublets)
    - Which well should be injector and producer? (**well type optimization)**

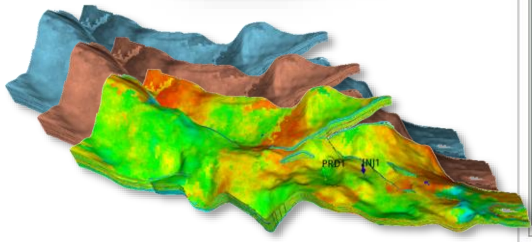


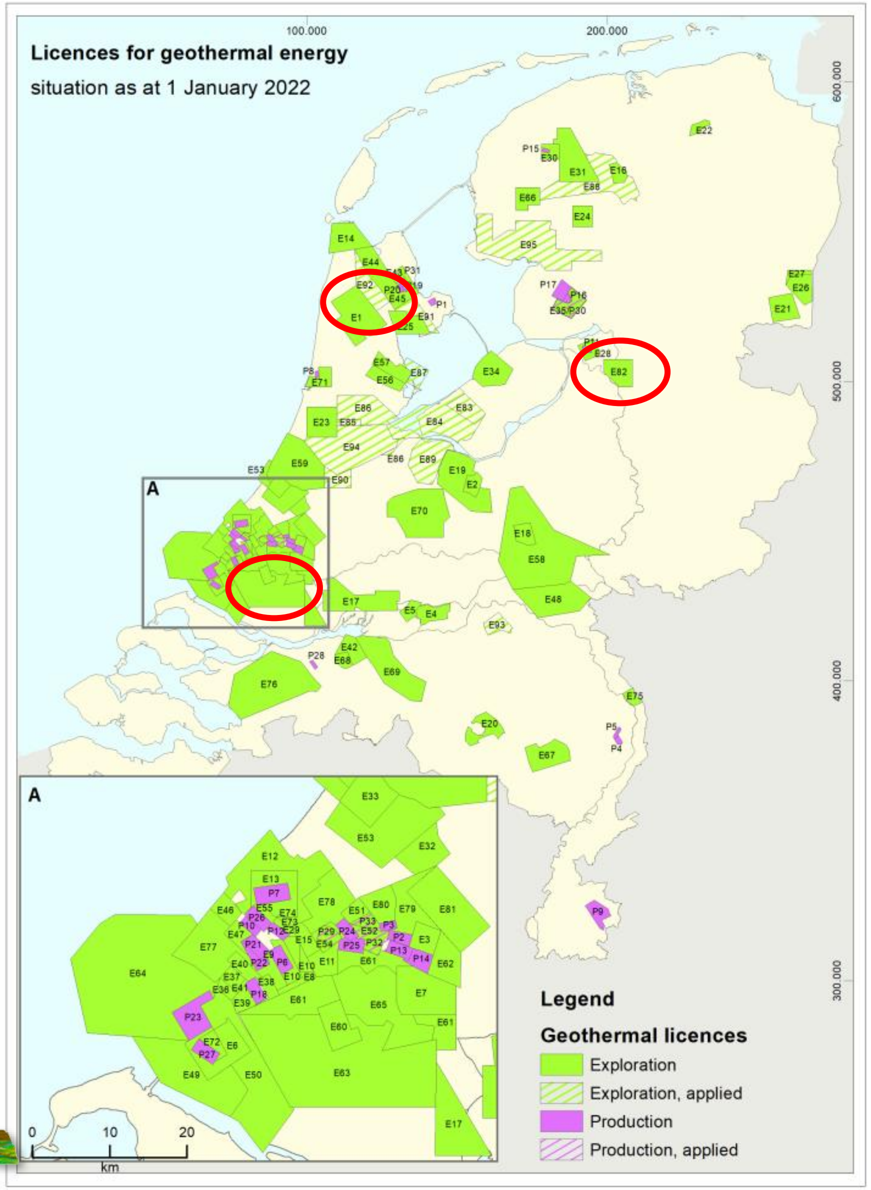
- **WarmingUP** Maasdijk**:** Plan to drill 6 wells (3 doublets)
    - **2 formations present without communication**
    - What production rates assign to the wells for each formation? (**well rate optimization)**



- **RESULT** Zwolle**:** Plan to place doublet
    - Where to place both wells
    - Deviated or horizontal or multilateral (**well location and trajectory optimization)**

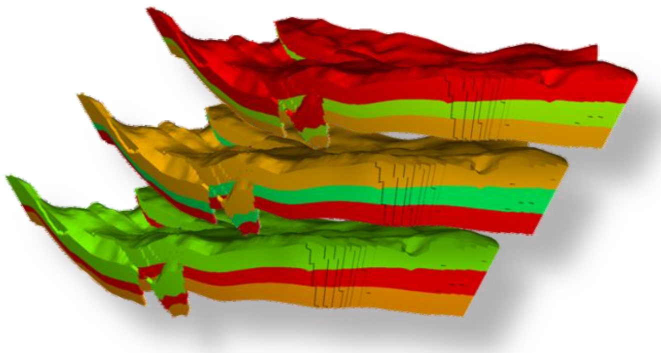
- **TKI UE** Middenmeer
    - High-temperature heat storage
    - Update models based on temperature observations (temperature data assimilation)

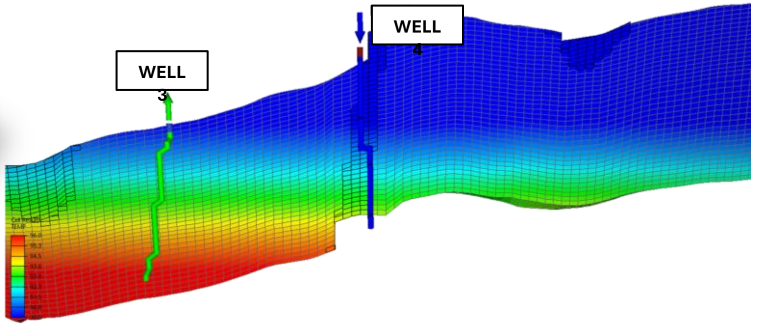


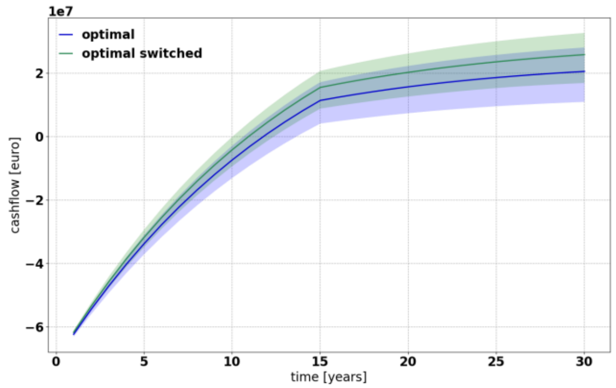


TKIGE: Well type optimization

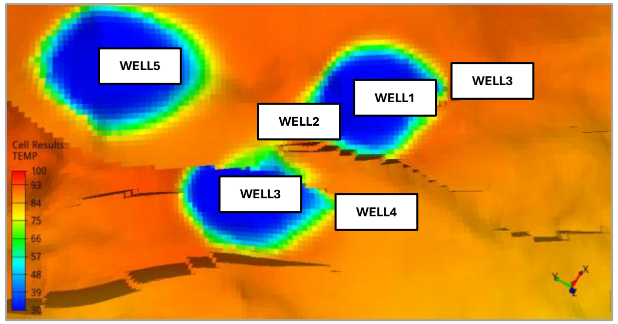
- Planned 6 wells, which well should be producer, and which should be injector.
- A more efficient well type configuration found benefitting from delay in cold water production.
- Ensemble of model realizations –> optimizing NPV on average across all models.
- Set of OPM Flow simulations at each iteration, reading SMSPEC/UNSMRY for production rates and temperatures to calculate extracted heat and subsequently the NPV.

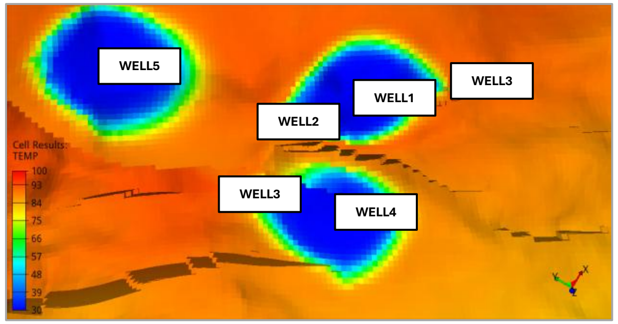


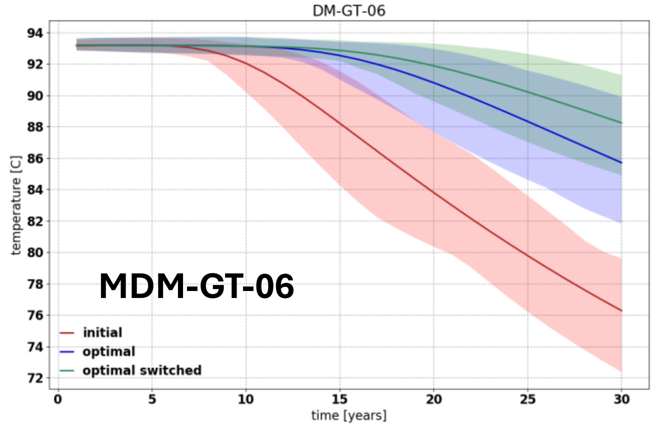




Results for 30 geological models







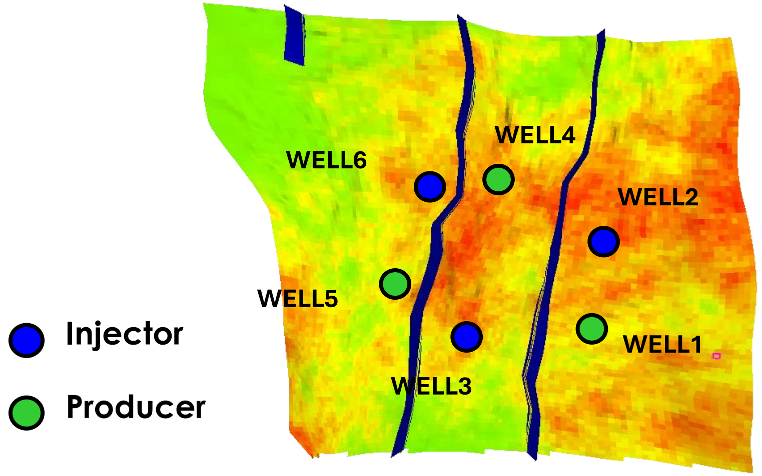
Group control for reinjection constraint

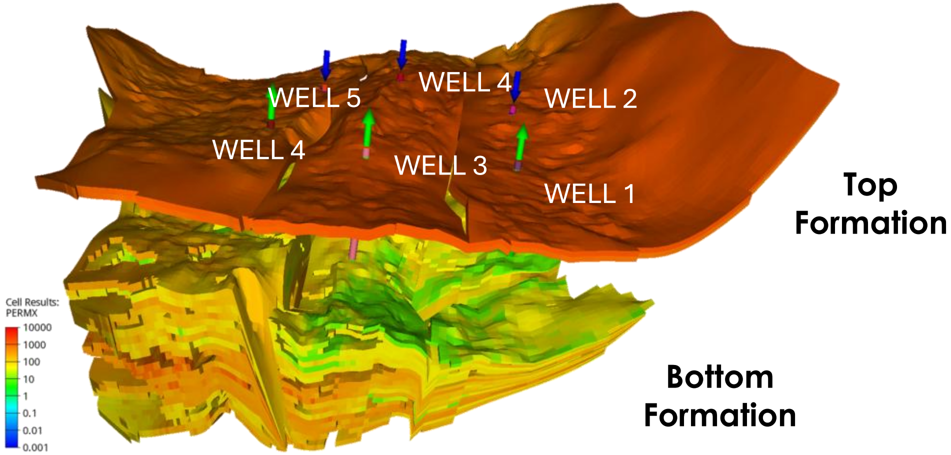
- Maintaining a balance where reinjection of cooled geothermal water equals extraction of hot water.
- In OPM Flow, **voidage replacement** is part of group control for injectors and producers.
- Maintain reservoir pressure by **balancing produced and injected volumes**.
- Injection rate is automatically adjusted so that **injected reservoir volume ≈ produced reservoir volume.**
- Requires proper **group hierarchy** (GRUPTREE).

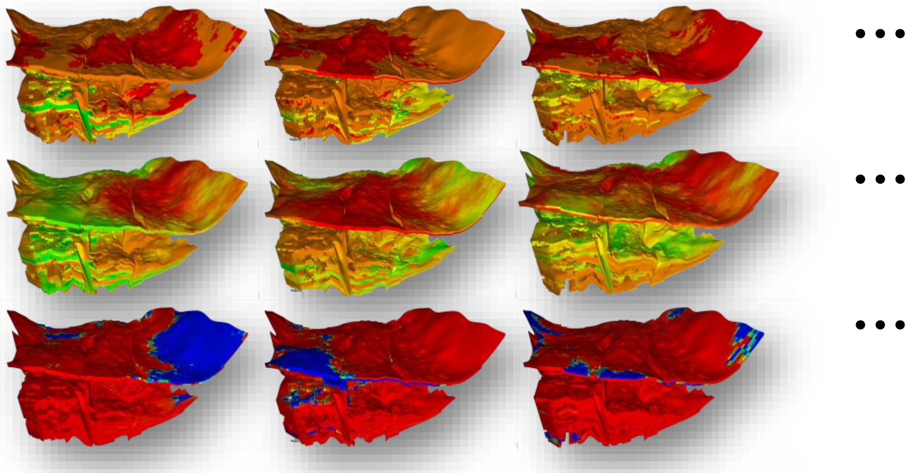
```
SCHEDULE

GRUPTREE
  'GROUP1' FIELD /
/
WCONPROD
  PRD1 OPEN BHP 1*  5000 3*  200 1* /
/
WCONINJE
  INJ1 WAT OPEN GRUP 5000 1* 300 1* /
/
WTEMP
  INJ1 30 /
/

GCONINJE
  'GROUP1'  WAT VREP 1* 2* 1.0 /
/
```

Warming UP: rate allocation optimization

- 6 planned deviated vertical wells (3 injectors and 3 producers), provided by operator.
- No communication between Top and Bottom formations.
- Uncertainty represented by ensemble of 40 different models.
- **What should be injection/production rates from each reservoir in the same well?**

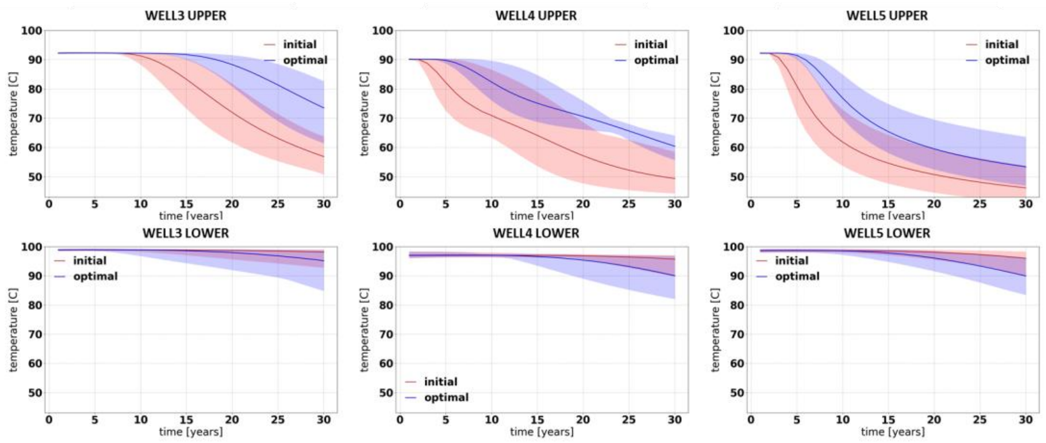


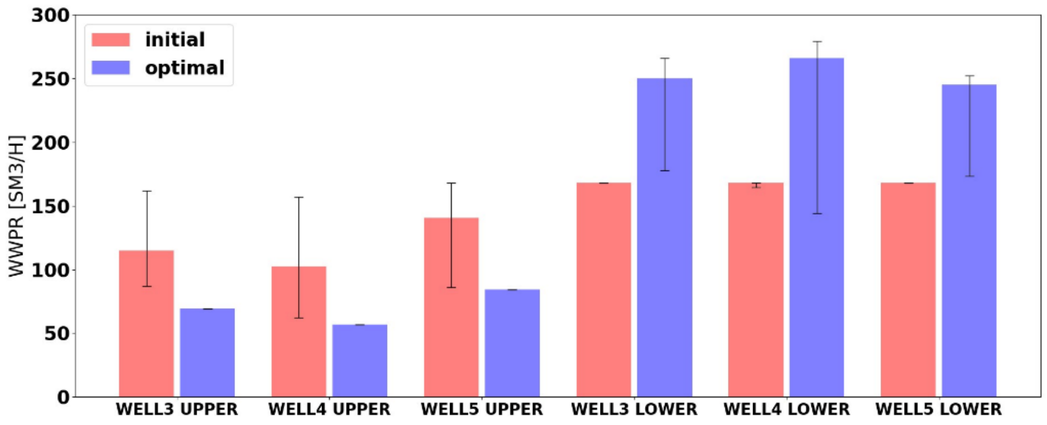




Warming UP: rate allocation optimization

- Significant increase of production rate targets in the Lower formation accompanied by a reduction of production in the Upper formation.
- More heat can then be extracted from the Lower formation.
- Decreasing flow rates in the wells in top formation delays the cold-water breakthrough in that formation.

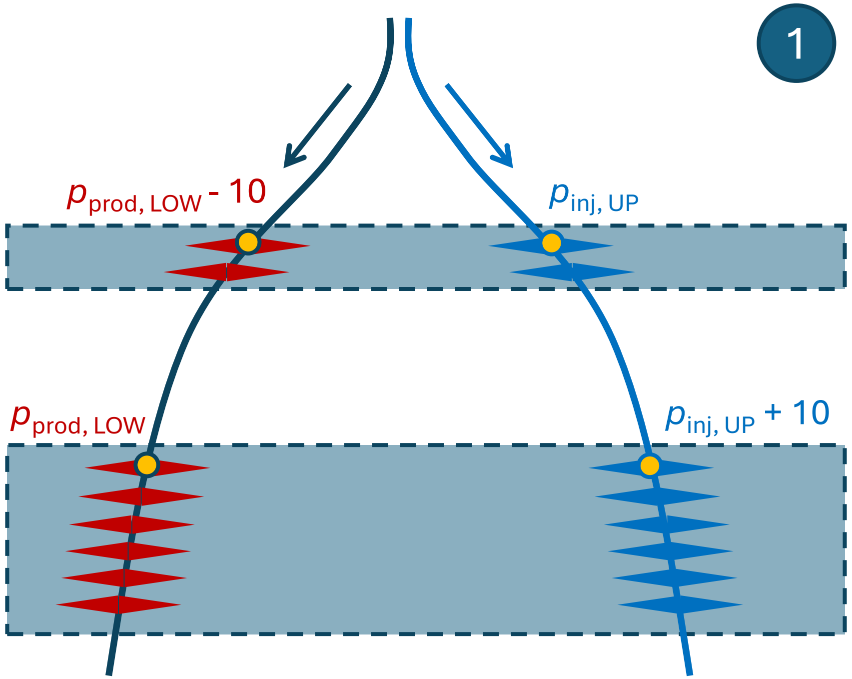




Warming UP: well pressure consistency

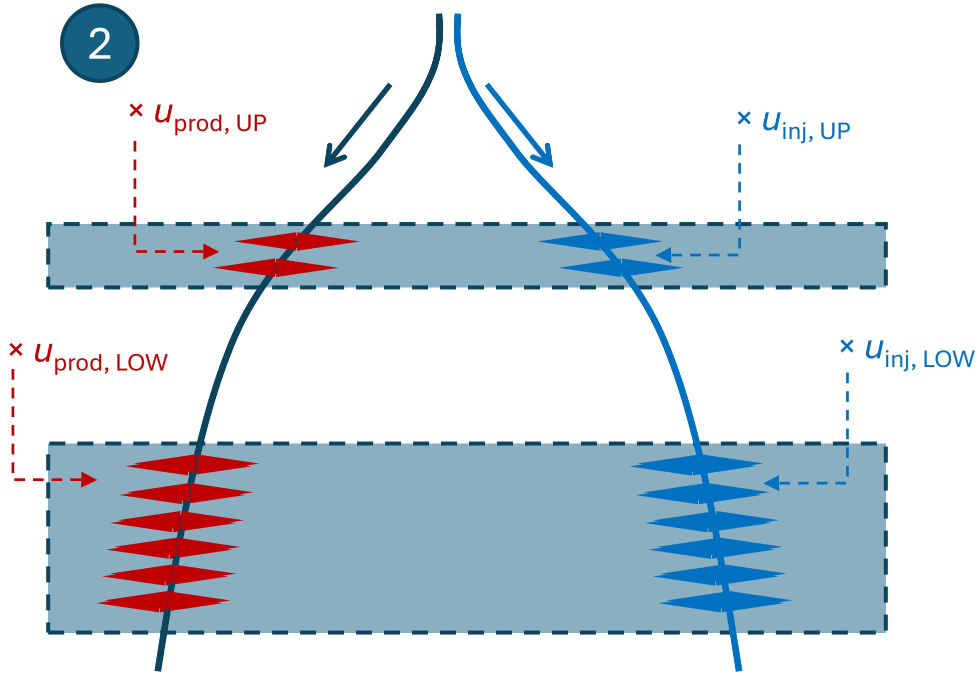
Well pressure consistency: two approaches within the reservoir simulator

Always imposing minimal difference between well pressure at both formations.



Splits well into two (one for each formation) and links the two BHP limits dynamically using UDQ functionality from simulator.

Controlling inflow of connections at upper formation.



Single well with two completion intervals: alter productivity of upper connections (partial choking) by applying connection factor multipliers ($0 < u < 1$).

Pressure consistency Approach #1

- Separately defined 12 simulation wells (6 wells in reality).
- Each well was split into two: a lower and an upper formation.
- UDQ keywords to ensure depth-consistent well pressure.
- We extract the current BHP for each well in one of the formation with UDQ and, based on this value, we set the constraint on the BHP in the other formation.
- Set realistic BHP constraints to the wells in the lower and upper formations individually.
- To ensure equal production and injection rates, we used the combination of UDQ and group-injection constraints (GCONINJE).
    - Gather the total production rate from each formation with an UDQ
    - Set that value as constraint for total injection rate in the same formation.

```
UDQ
  DEFINE GUPRODU (GUPR 'GROUPU') /
  DEFINE GUPRODL (GUPR 'GROUPL') /
/
GCONINJE
  GROUPU WATER RATE GUPRODU 2* 1.0 /
  GROUPL WATER RATE GUPRODL 2* 1.0 /
/
UDQ
  -- example producer
  DEFINE WUPRODL1 (UBHP 'MSDGTU01' + 10) /
  -- example injector
  DEFINE WUINJU2 (WBHP 'MSDGTL02' - 10) /
/
WCONINJE - example injectors
  MSDGTU02 WATER 1* GRUP 8400 1* WUINJU2 /
  MSDGTL02 WATER 1* GRUP 8400 1* 290 /
/
WCONPROD - example producers
  MSDGTU01 1* WRAT 1* <rate_U01> 3* 210 /
  MSDGTL01 1* WRAT 1* <rate_L01> 3* WUPRODL1 /
```

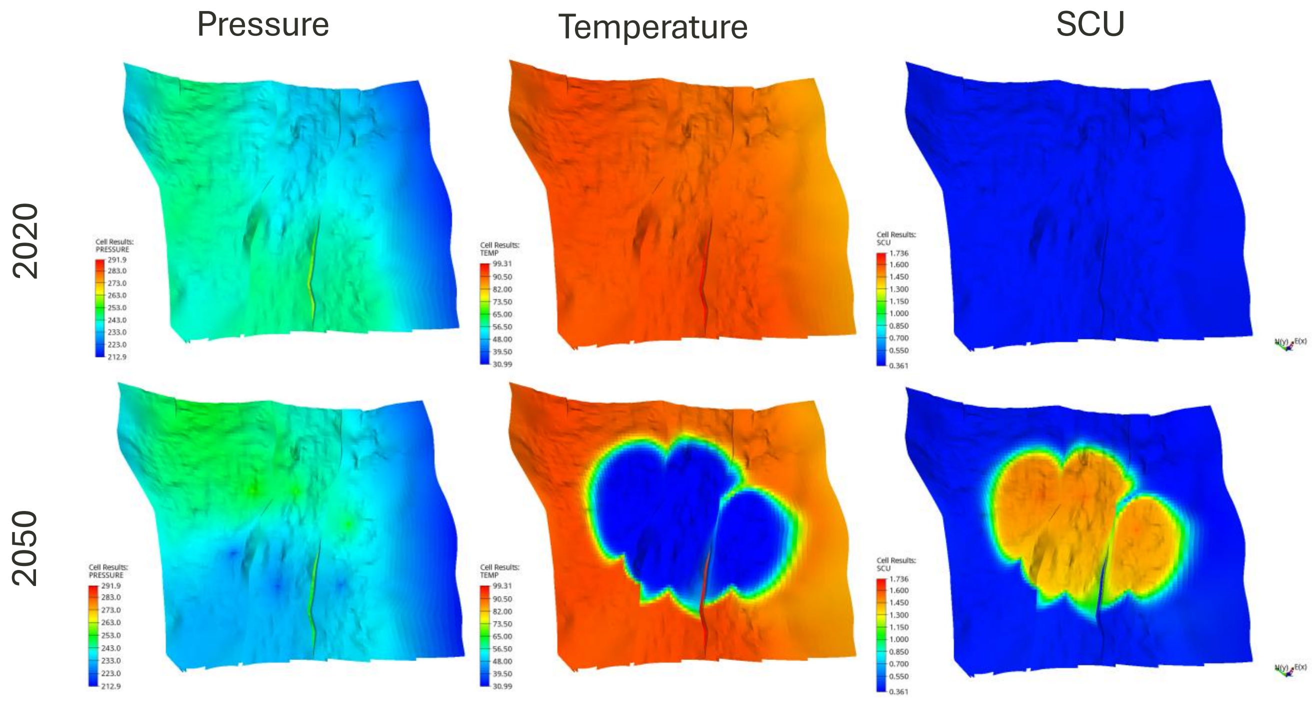
Pressure consistency Approach #2

- An alternative approach can be to **optimize well productivity index multipliers** - equivalent to optimizing well production rates.
- **Lumped the well connections** together into completions for simultaneous closure in automatic workovers.
- **Each well has two completion sets corresponding to the perforations in each formation** to ensure the control on flow capacity of each formation.
- We interact with the **WPIMULT** keyword (which applies a multiplier to the well connection factors) instead of optimizing the rates.
- The combination of UDQ and **group-injection** constraints were included to guarantee equal production and injection within the same formation.

```
GRUPTREE
  'GROUPI' FIELD /
  'GROUPP' FIELD /
/
COMPLUMP -- example
  MSDGT01 2* 2 3  1  /
  MSDGT01 2* 5 23 2  /
/
UDQ
  DEFINE GUPRODU (GWPR 'GROUPP’) /
  UNITS GUPRODU SM3/DAY /
/
GCONINJE
  GROUPI WATER RATE GUPRODU 2* /
/
WCONPROD – example producer
  MSDGT01 1* WRAT 1* 8400 3* 210 /
/
WCONINJE – example injector
  MSDGT02 WATER 1* GRUP 8400 1* 290 /
/
WPIMULT -- example
  MSDGT01 <wpimult_11> 1* 1* 1* 1  1  /
  MSDGT01 <wpimult_12> 1* 1* 1* 2  2  /
/
```

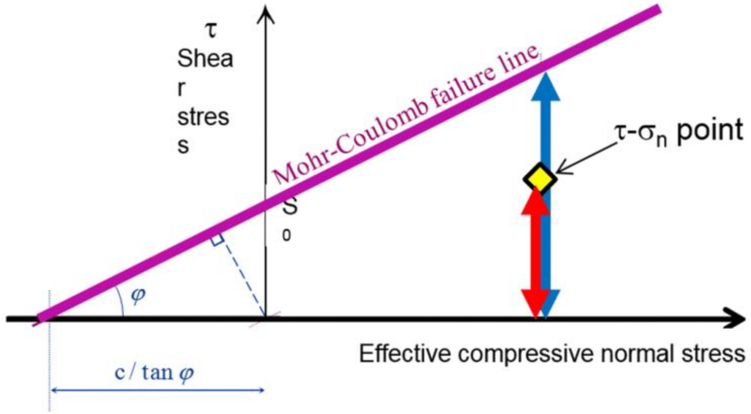
Geomechanical constraints

- Use geomechanical parameter (Shear capacity Utilization) as constraint in optimization:
  - Read temperature and pressure from the grid.
  - Write SCU into a new EGRID file (our own code to edit binaries).



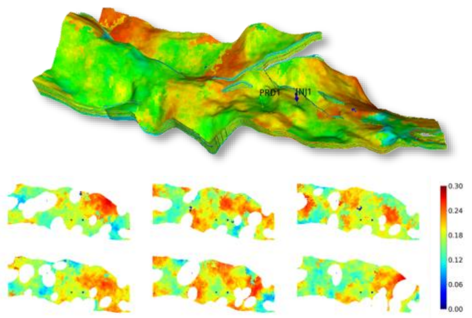
SCU < 1: No shear. SCU =1 is the onset of shear failure

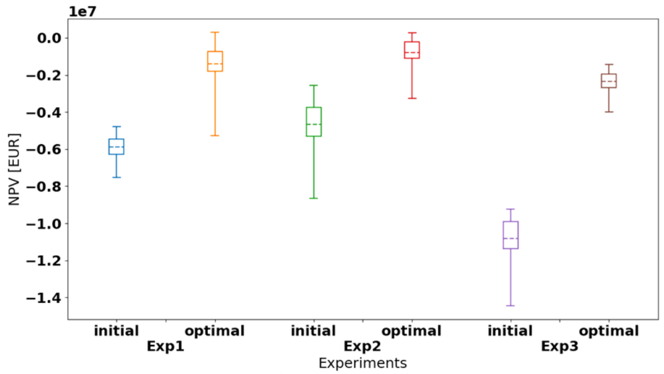
$$SCU = \frac{L_{unfaulted}}{L_{faulted}} = \frac{\tau_{max}}{S_0 + (\sigma_n \tan \varphi)}$$

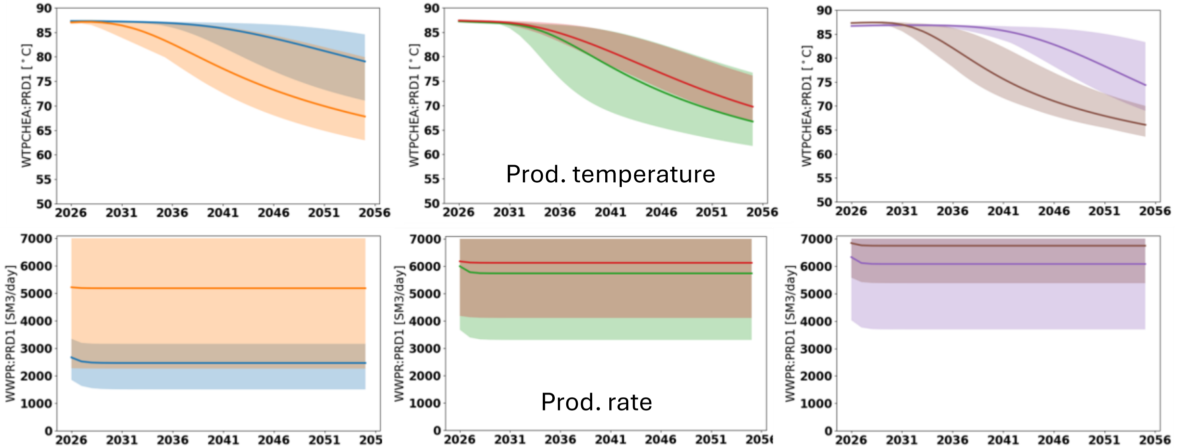


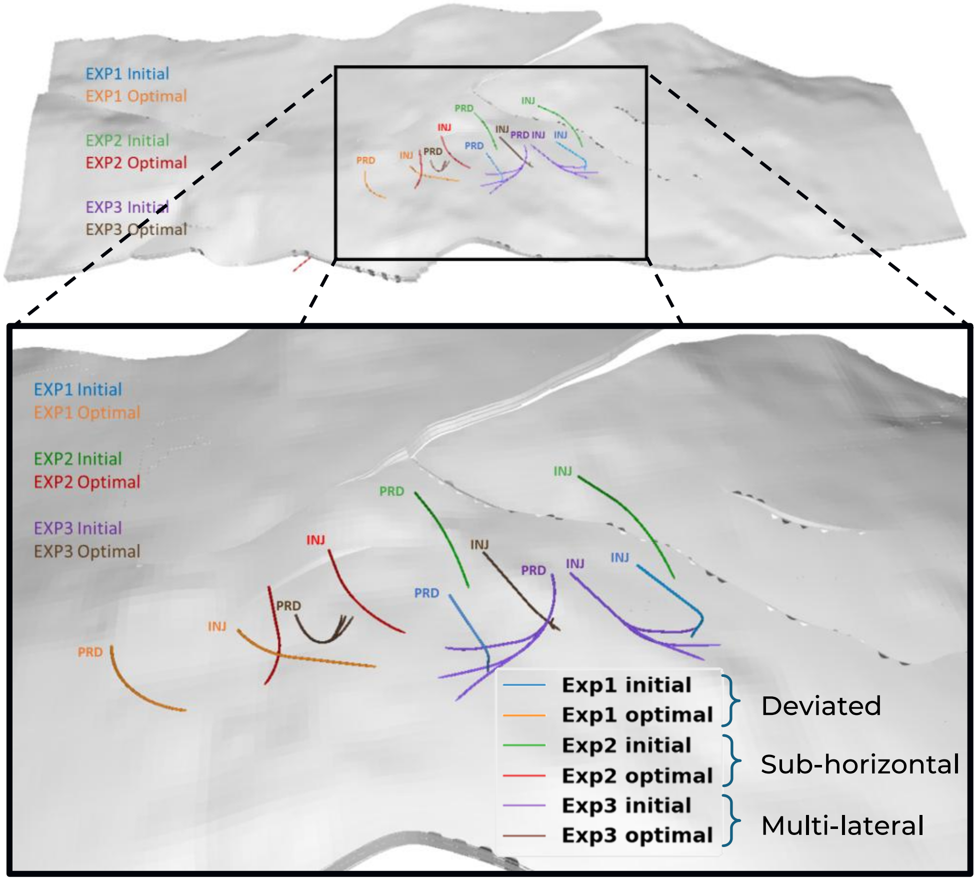
RESULT: well trajectory optimization

- Three concepts considered: slightly deviated, strongly deviated, multilateral.
- Optimization found better solutions in terms of NPV for horizontal and multilateral wells for marginal reservoirs.
- The balance between production rates and temperature.

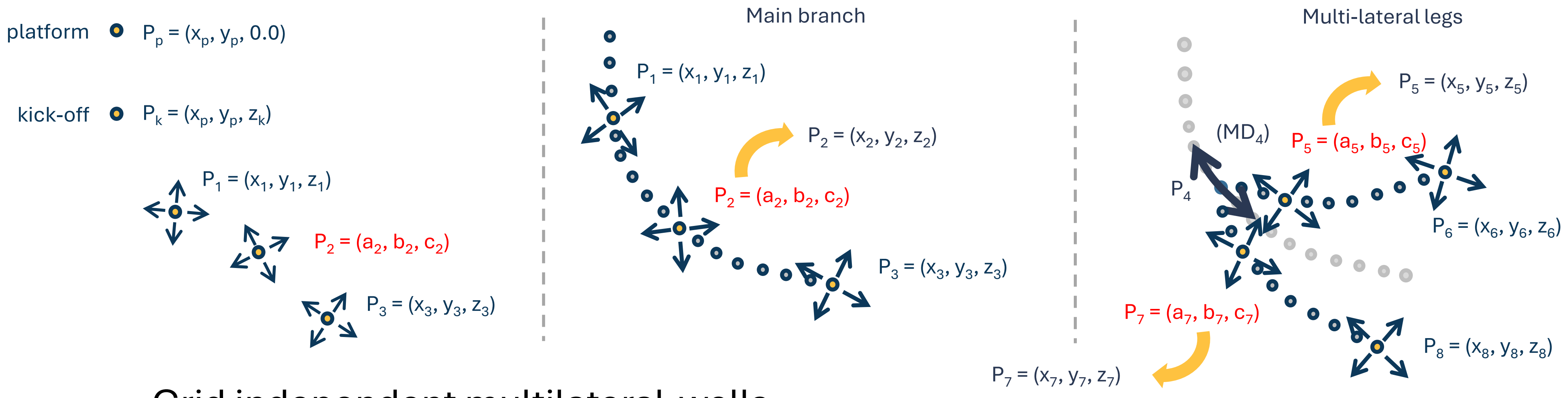




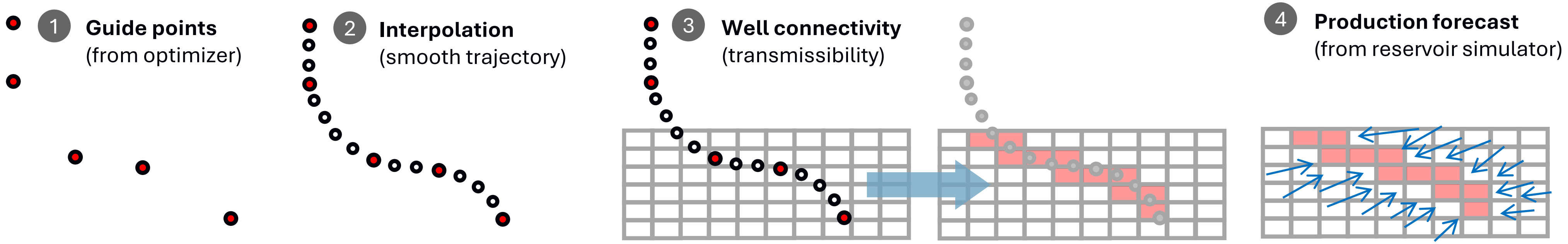




Well trajectory: parametrization



Grid independent multilateral-wells



Well trajectory: from guide points to connections

For each numerical model and for each well path

Well path in 3D space is generated by EVEREST: guide points only.

```
"INJ-01": [
    [ 138993, 138993, 138162, 138101, 138040 ],
    [ 486525, 486525, 487156, 487221, 487286 ],
    [ 0,          300,    1835,    1896,    1957 ]
 ]
```

Well path in 3D space interpolated by ResInsight or python script.

```
WELLNAME: 'INJ-01'
#           X              Y        TVDMSL        MDMSL
  139038.63      486490.94         0.00         0.00
  139038.53      486491.02         5.00         5.00
  139038.42      486491.09        10.00        10.00
  139037.06      486492.11        44.94        45.00
  139032.98      486495.16        89.63        90.00
```

Log file generated by ResInsight, comparing well trajectory against the grid.

```
~Curve information
DEPTH .M   : Depth in meters
TVDMSL .M  : True vertical depth in meters
TVDRKB .M  : True vertical depth (Rotary Kelly
Bushing)
Active_Formation_Names .NO_UNIT  :
#
~Ascii
1792.105 1539.814 1539.814 0.000
1800.568 1546.842 1546.842 0.000
1800.568 1546.842 1546.842 0.000
1882.851 1615.172 1615.172 0.000
1882.851 1615.172 1615.172 0.000
1906.686 1634.965 1634.965 0.000
```

Connection factors/ segment information exported by ResInsight.

```
-- WELL    GROUP          BHP    PHASE  DRAIN  INFLOW  OPEN  CROSS  PVT    HYDS  FIP
-- NAME    NAME    I   J   DEPTH  FLUID  AREA   EQUANS  SHUT  FLOW   TABLE  DENS  REGN
WELSPECS
   PRD-01  GROUP1      18  56  1*     WATER    1*      STD     STOP  YES    0      SEG   0     /
/
-- WELL                            OPEN  SAT   CONN          WELL      KH            SKIN     D     DIR
-- NAME     I    J     K1    K2    SHUT  TAB   FACT          DIA       FACT          FACT     FACT  PEN
COMPDAT
   PRD-01   17   54    4     4     OPEN  1*    4.886493E+00  0.30000   4.559725E+02  0.00000  1*    'Z'  /
```

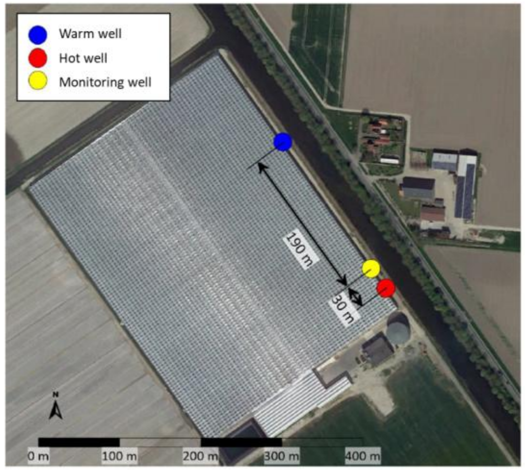
```
WELSEGS
-- Well       Dep 1          Tlen 1        Vol 1      Len&Dep     PresDrop
   PRD-01     1617.75512     1619.55324    1*         ABS         'HF-'     /
-- First Seg       Last Seg      Branch No     Outlet Seg      Length          Depth Change      Diam       Rough
   2               2             1             1               1634.71233      1632.88053        0.15200    0.00001
/
```

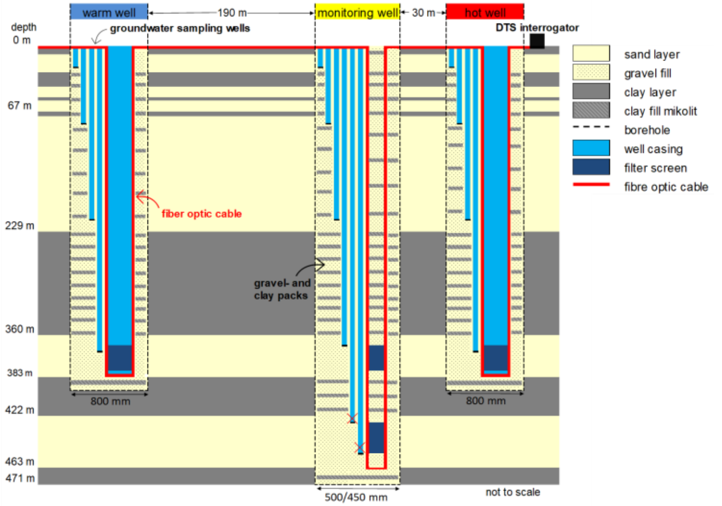
```
COMPSEGS
-- Name
   PRD-01 /
-- I      J      K      Branch no      Start Length      End Length
   17     54     4      1              1915.96121        1922.29600      /
/
```

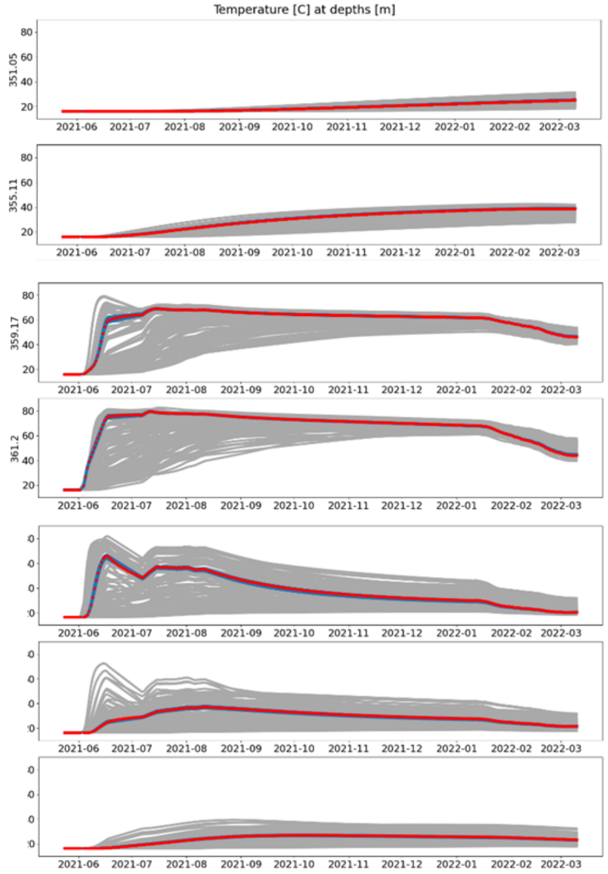
Currently using ResInsight as background service – not ideal.

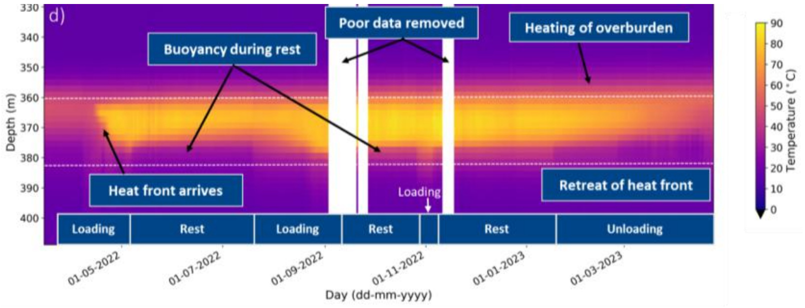
DTS data assimilation for heat storage

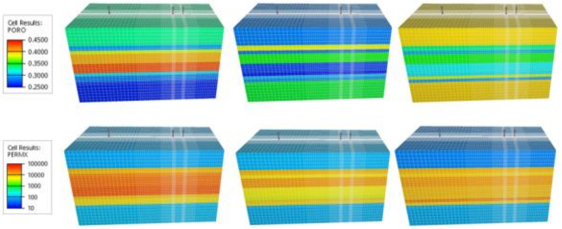
- Numerical models are used for the prediction of thermal behaviour in the high temperature aquifer thermal energy storage (HT-ATES).
- Models updated in data assimilation based on distributed temperature sensing (DTS) data from cable along the monitoring well.
- ACTIONX/pyAction useful here to automate stopping heat extraction when efficiency below economic limit.











Geothermal relevant modelling features

- Modelling features important for Dutch geothermal scenarios.
- Challenges in numerical performance (when frequent rate changes or relatively larger grid cells).

```
VISCREF
-- Water properties for various regions in the model.
-- Item (1) reference pressure for the viscosity and temperature tables (Barsa)
--      (2)  reference gas-oil ratio for when the model contains gas dissolved(-)
-- REFPRES   REFGOR
35.0 0.0001 /
```

```
WATVISCT
-- Water properties
-- Item (1) temperature (deg C)
--      (2) water viscosity (cP)
-- WATERTEMP   WATERVISC
10          1.26
15          1.11
/
```

```
WATDENT
  1* 1* 1*/
```

```
DENSITY
-- Surface densities of the fluids
-- Item 1: surface oil density (kg/m3)
-- Item 2: surface water density (kg/m3)
-- Item 3: surface gas density (kg/m3)
859.5 1010.95 0.854 /
```

```
SPECHEAT
-- Specific heat of oil water and gas phases
-- Column 1: Temperature [deg C]
-- Column 2: Specific heat capacity of oil [kJ/kg/K]
-- Column 3: Specific heat capacity of water [kJ/kg/K]
-- Column 4: Specific heat capacity of gas [kJ/kg/K]
10            0.5          4.084        0.25
20            0.5          4.084        0.25
/

ROCK
-- Rock compressibility
-- Item 1: reference pressure (barsa)
-- Item 2: rock compressibility (1/barsa)
50.0 1E-5 /

SPECROCK
-- Specific heat of reservoir rock
-- Column 1: Temperature [deg C]
-- Column 2: Specific heat of the reservoir rock [kJ/m3/K]
0 2334
100 2334/
```

Summary

- Context which features is relevant for Dutch geothermal applications and to us and how we use them:
  - e.g., temperature modelling, LGR, grid independent wells, python interface, etc.

- Our team has been involved in development (not only for geothermal features) and continue to do so.
- OPM Flow is core part of our uncertainty based closed loop reservoir management workflows.
  - Ensemble of simulations required at each iteration.
  - This allows us to stay active in benchmarking and bug reporting.

- Relatively complete set of feature for Dutch geothermal scenario.
- Current challenges rather in numerical performance.