Utilization of distributed fiber optic monitoring in reservoir section

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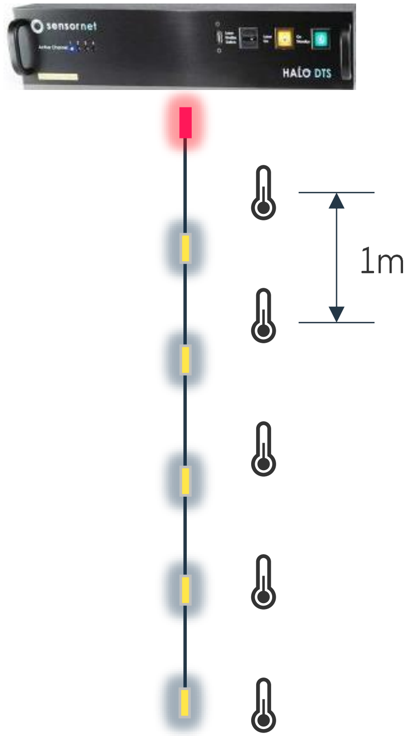
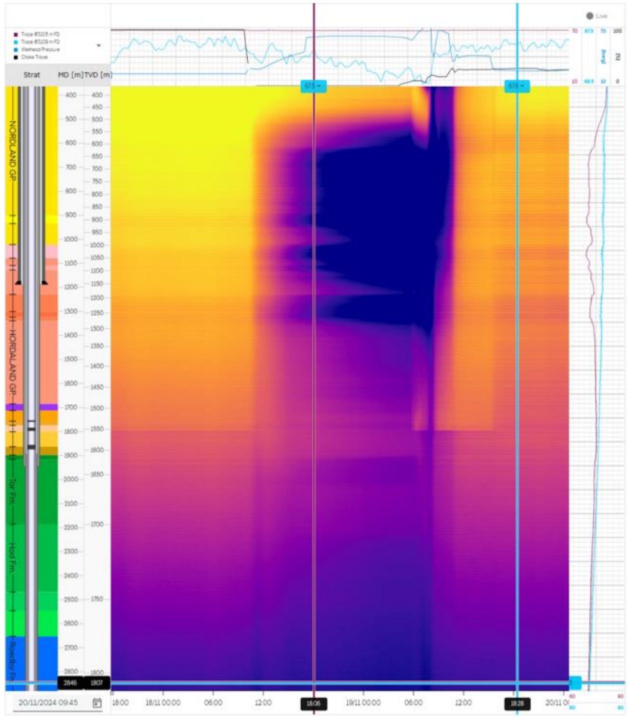
Distributed Fiber Optic Measurements –Basics Recap

- DTS (Distributed Temperature Sensing)

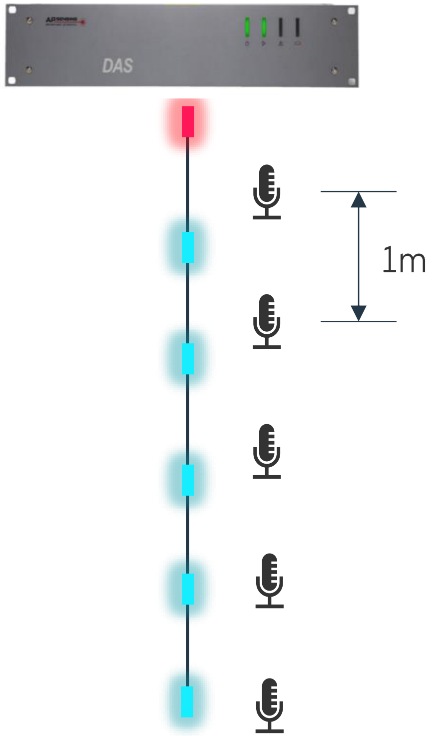


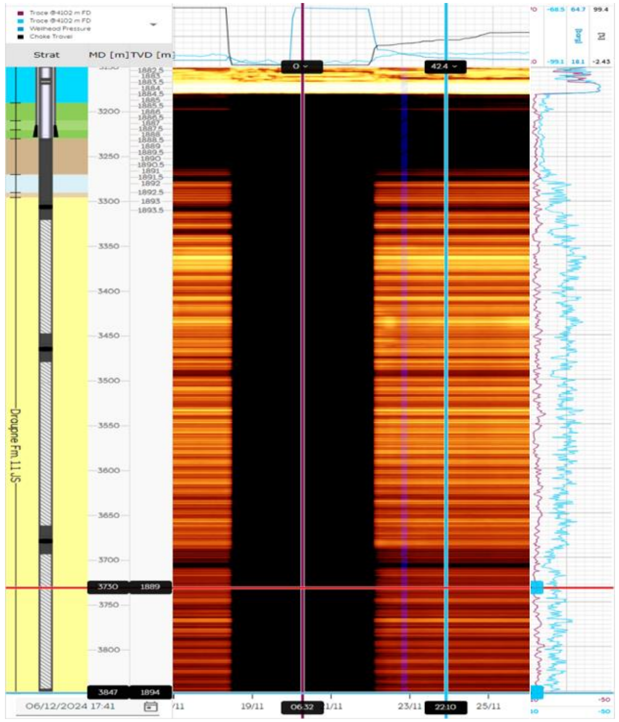


Frequency shift of (Raman) backscattered light used to measure temperature

- Temperature output every 0.25m / approx every minute

- DAS (Distributed Acoustic Sensing)





Phase lag of (Rayleigh) backscattered light used to measure ´acoustic´ strain

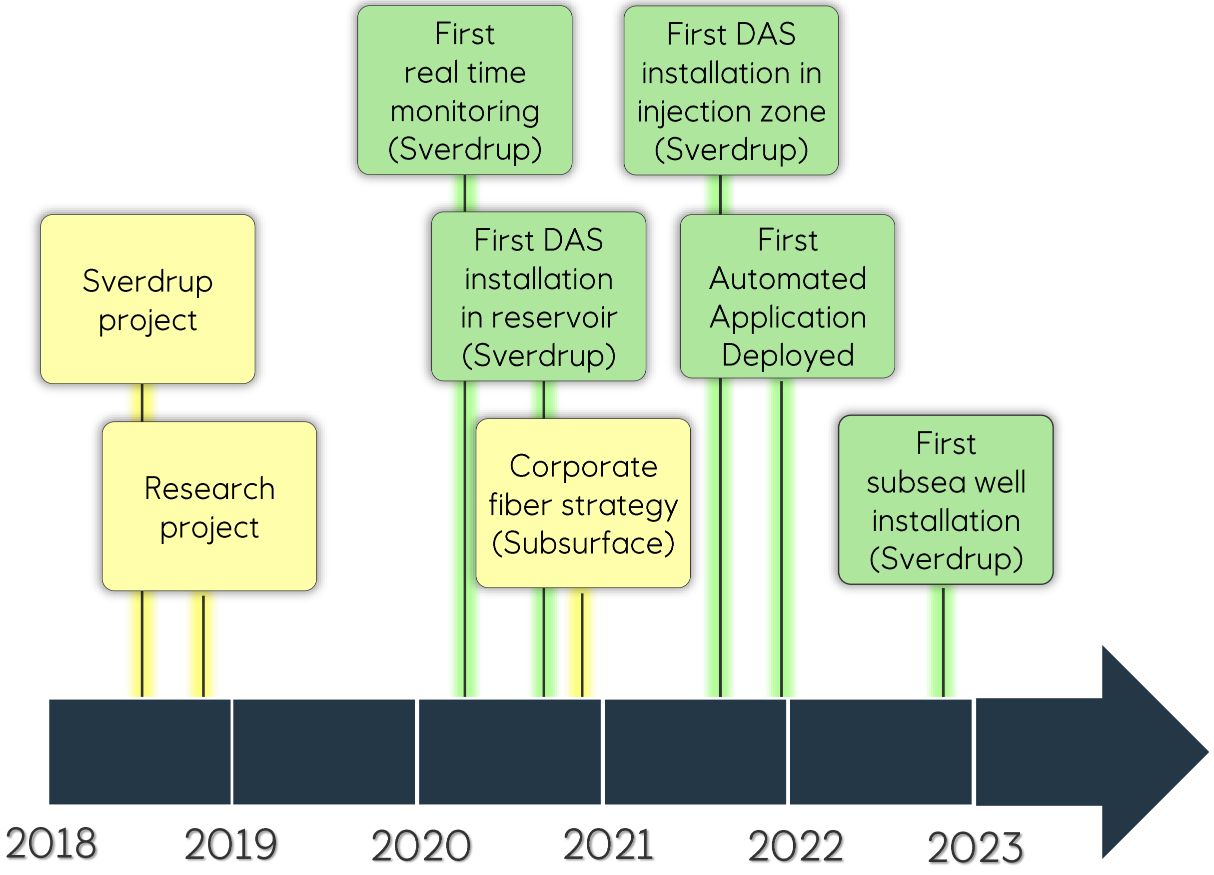
- 20kHz sampling frequency (10kHz Nyquist)
- Full frequency spectrum processed into Frequency band energy (FBE) features e.g. (10-20 Hz, 100-200Hz)
- FBE features output approx every meter/ every second

Introduction – Equinors Fiber Optic Journey

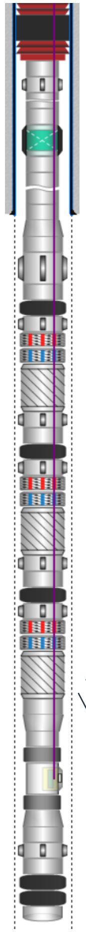
- Equinor has had some FO experience prior to the Johan Sverdrup Field Development
  - Permanent in-well DTS on two fields
  - Campaign based FO acquisition (on DHPG fiber cables)
  - DAS VSP Acquisition

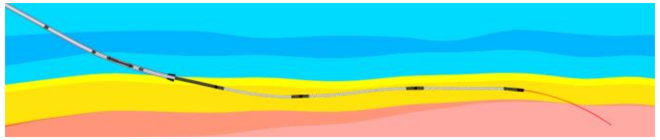
- Johan Sverdrup field development – large scale permanent in-well fiber monitoring
  - 30+ wells with fiber (DAS/DTS) installed to production packer
  - DAS VSP Acquisition (2019)
  - 2 wells with fiber in the reservoir (many trials, but not many successes)
    - 1 oil producer (First FO data in Nov 2020)
    - 1 water Injector (First FO data in Nov 2021)

- Aim to provide some insights from DFO measurements in the two wells with reservoir installations
  - Observations
  - Analysis /Interpretation
  - Application development



Producer with ICDs



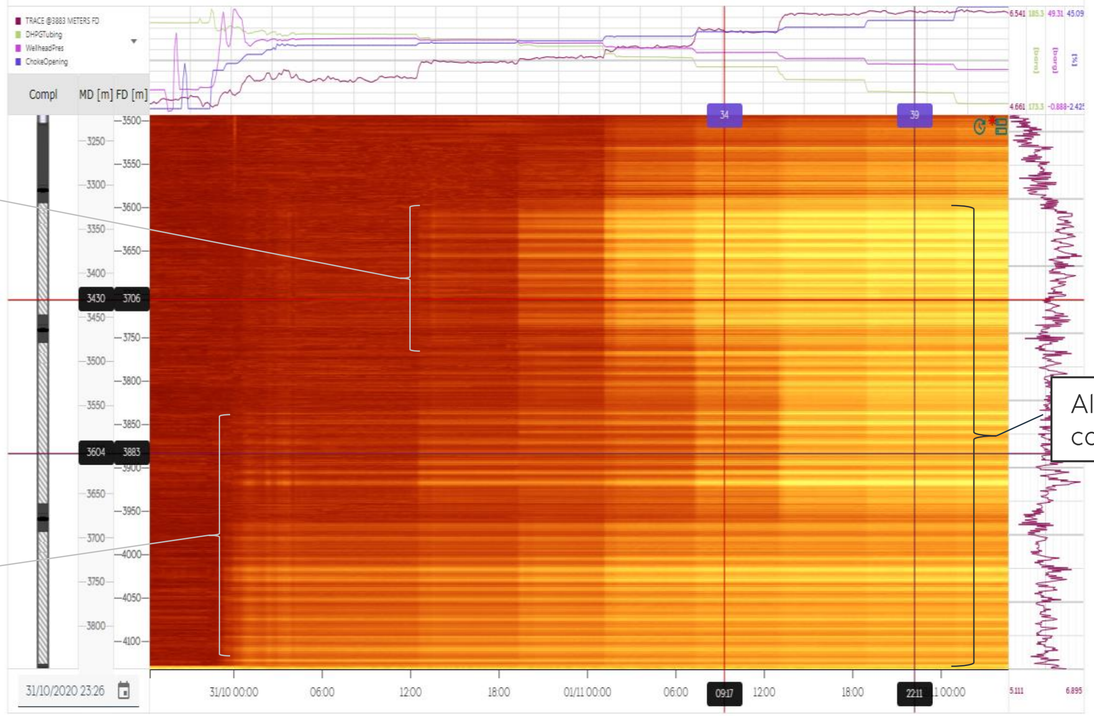


- 400m long, horizontal, reservoir section
- Open hole screen completion
- Three production zones separated by packers
- 40 ICD's in total (13, 16, 11 in each zone respectively)
- Production start Nov 2020
- Single phase oil until first water production in June 2021 (water cut - max 4%)
- DAS (Constellation fibre) / DTS

Inital DAS observations during well clean up

As drawdown / flow increases we get more contribution from the heel

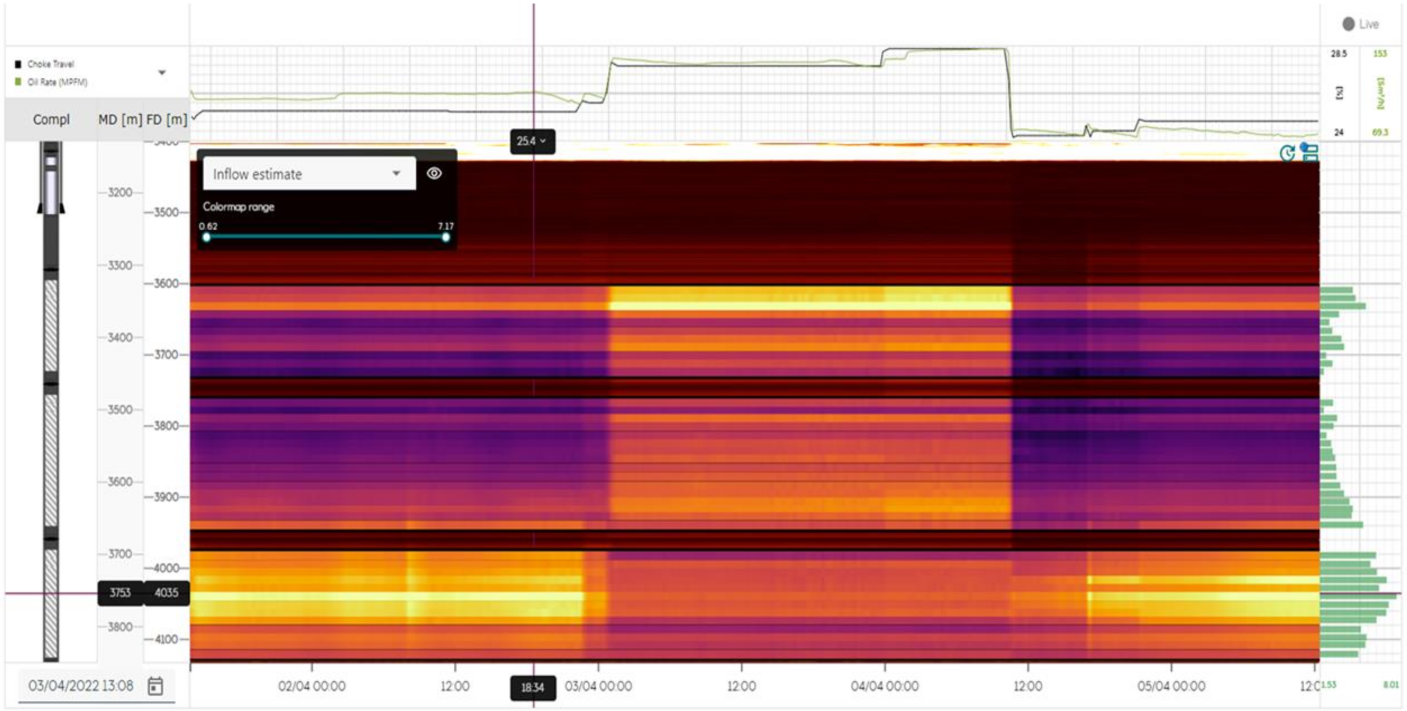
First contribution from the toe / middle section



All zones contributing

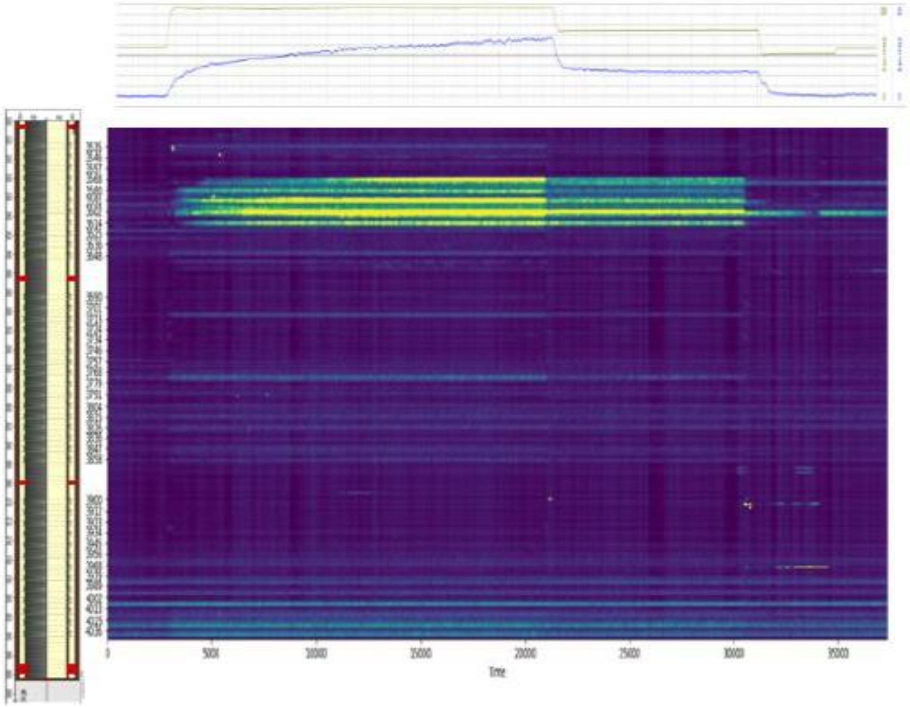
Continuous Inflow Profiling Application (single-phase oil)

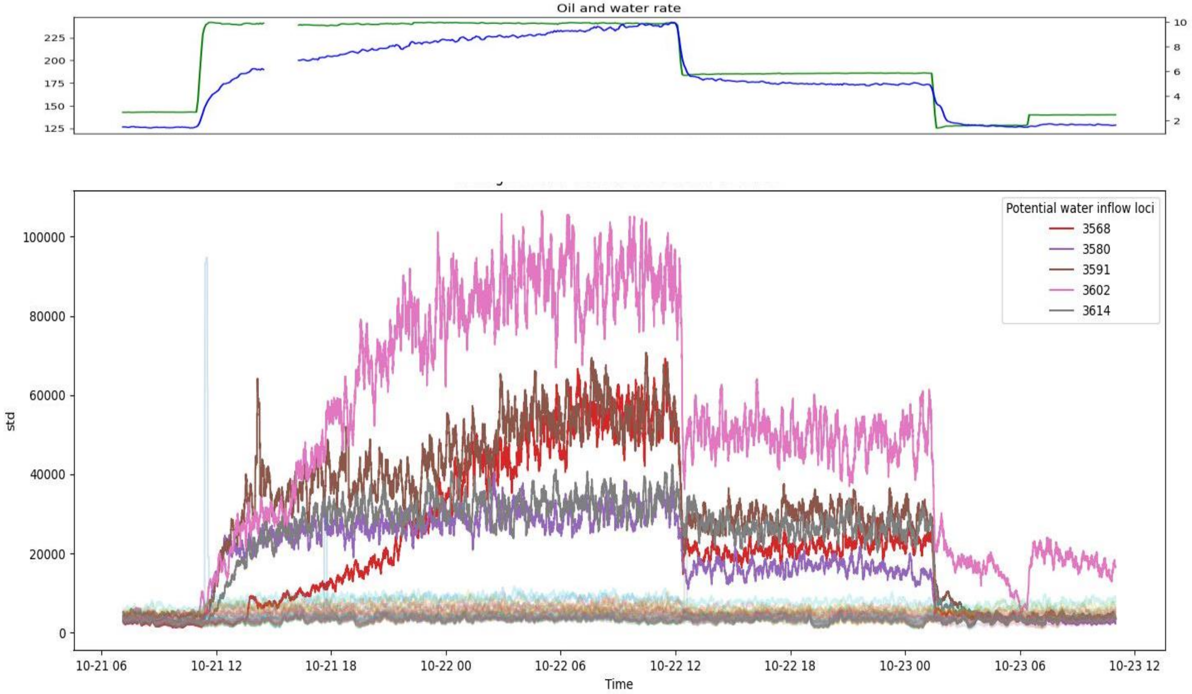
- Inflow app deployed on fotone platform via an "application framework"
- Model runs continuously as processed data live streams arrive
- Continuous inflow profile outputs
- User can visualise outputs as:
    - Colour map overlay
    - Traditional PLT display
        - Contribution per ICD
        - Cumulative inflow
- Continuous QC: predicted rate vs MPM rate
    - Cumulative rate estimate still matches measured liquid rate (oil + water) well even after water breakthrough (for small/moderate water cut).
    - The error gets larger when water cut increases further, and model adaptation is needed.



Signature of water in the LF-DAS

■: oil rate ■: water rate

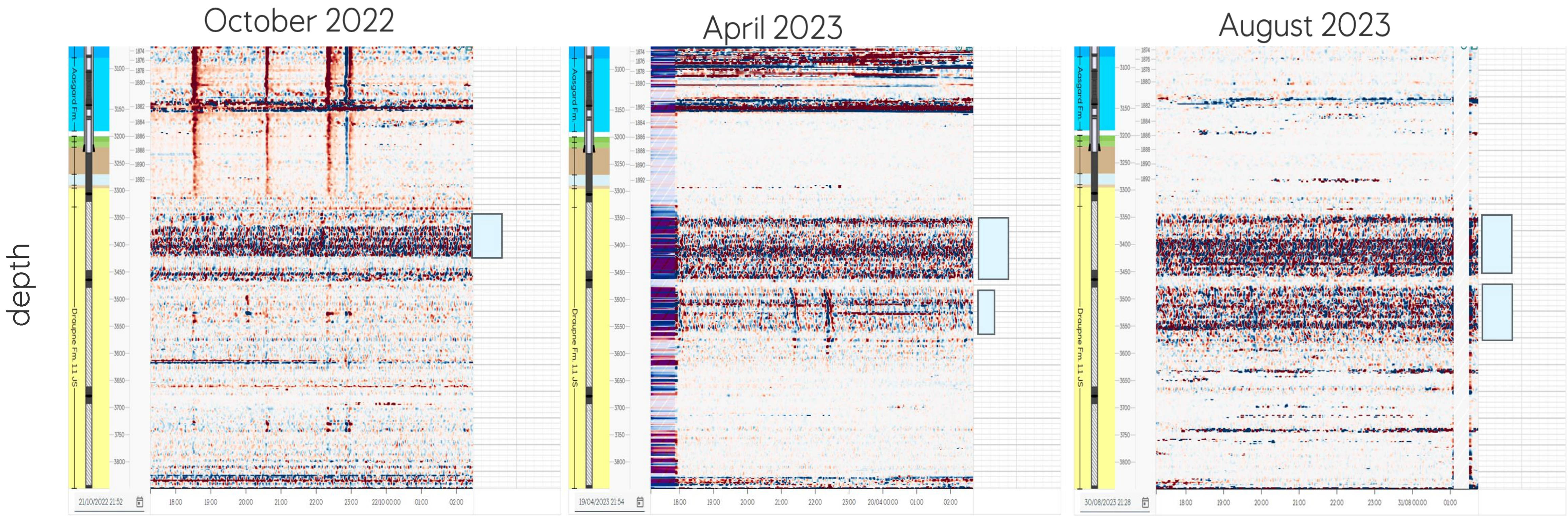




A statistics of the LF-DAS responding to the variation of water rate

*LF-DAS: Low-frequency (< 1 Hz) content in the DAS

Development of water inflow



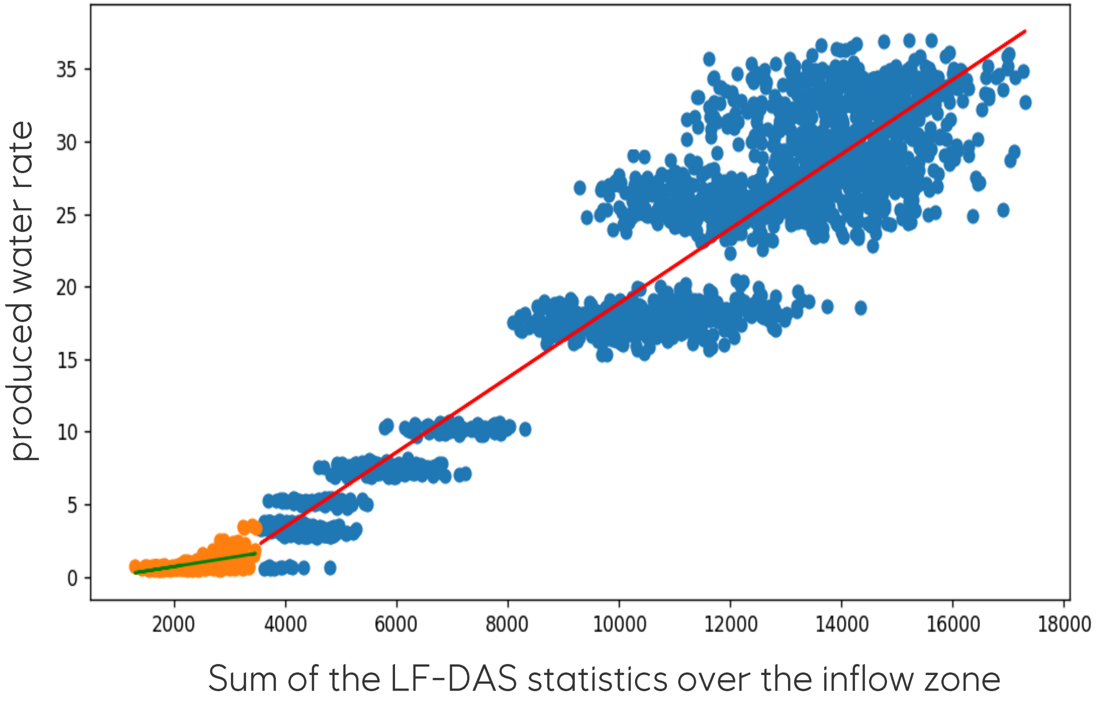
Very small water-cut

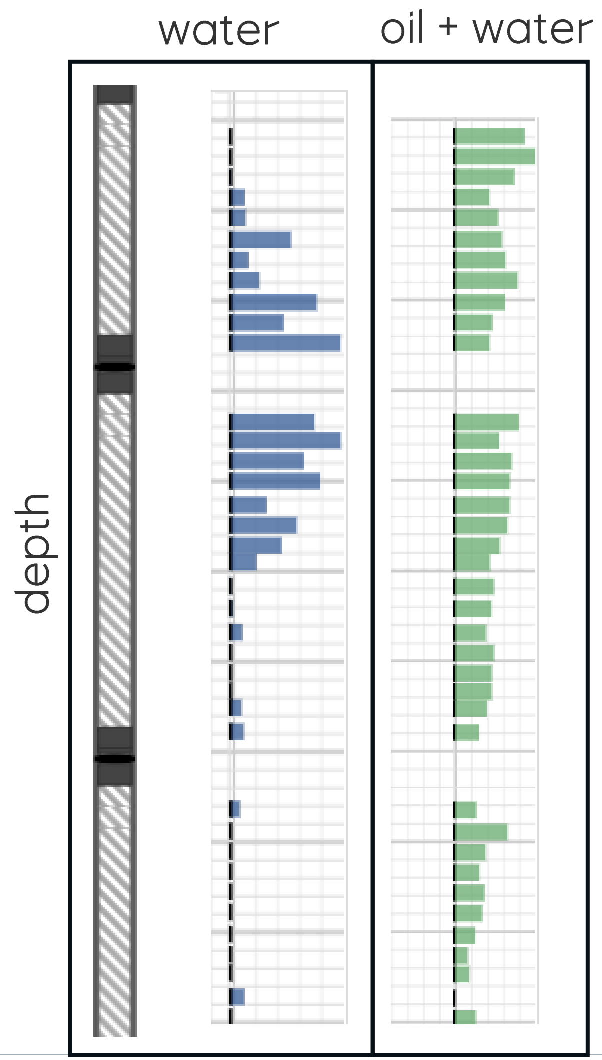
Small water-cut

Moderate water-cut

- The identified depth interval with water production extends, as time moves forwards, from the shallow part towards the deeper part of the inflow interval of the well.

Estimates of water and oil inflow





- Linear and nonlinear correlations investigated
- Top-side rate used to calibrate
- To be verified by PLT´s

An injector with sand screen

Well completion info:

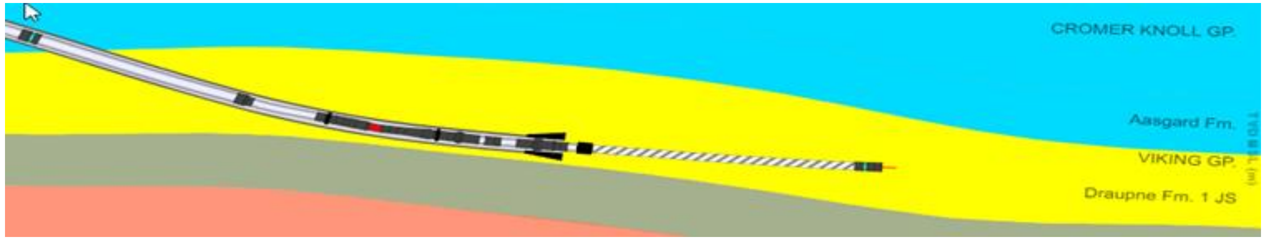
- ~100m long reservoir section (almost horizontal)
- Single injection zone
- Open-hole screens (9 screen joints)

Reservoir info:

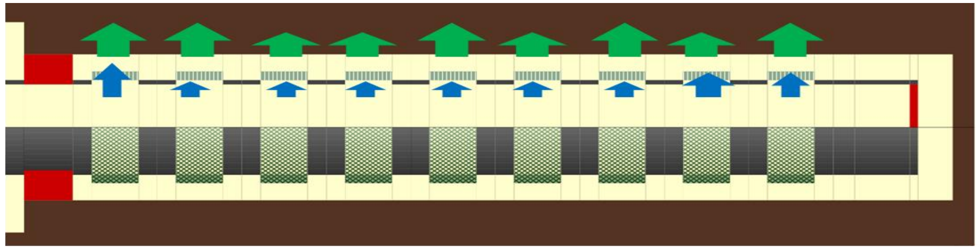
- High permeability (up to 20 Darcy)

Difference in injection profiles:

- The AR-profile is mainly determined by the permeability profile
- The TA-profile peaks at the first joints



Annulus-to-reservoir (AR) profile

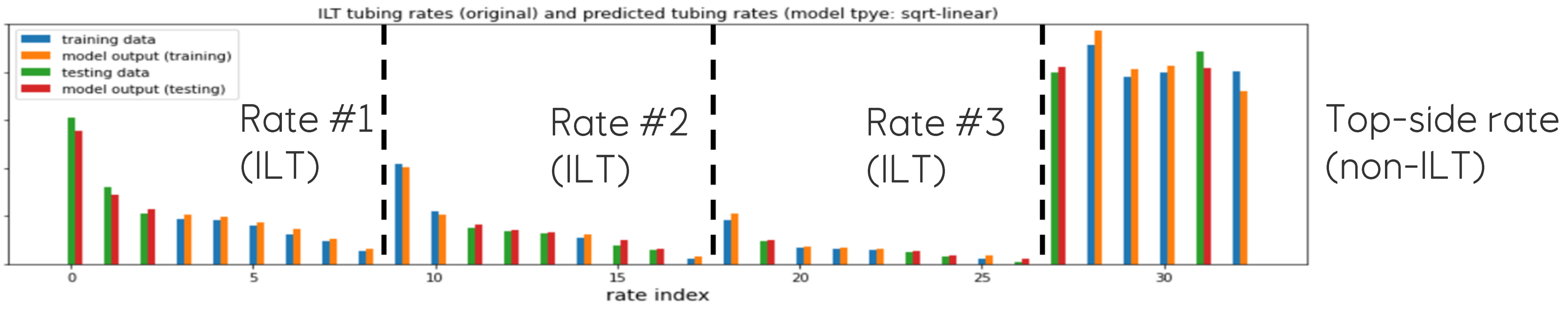


Tubing-to-annulus (TA) profile

Injection Outflow Profiling: FBE-based method for TA-profile

- **Challenges in applying the previous method for inflow profiling:**
  - The water outflow through the screens does not make as distinctive frequency contents as the oil does when it flows through the ICDs
  - It is difficult to remove the noise corresponding to acoustic waves travelling in tubing and annulus

- **Indirect estimation of outflow profile by utilising information from simulation model**



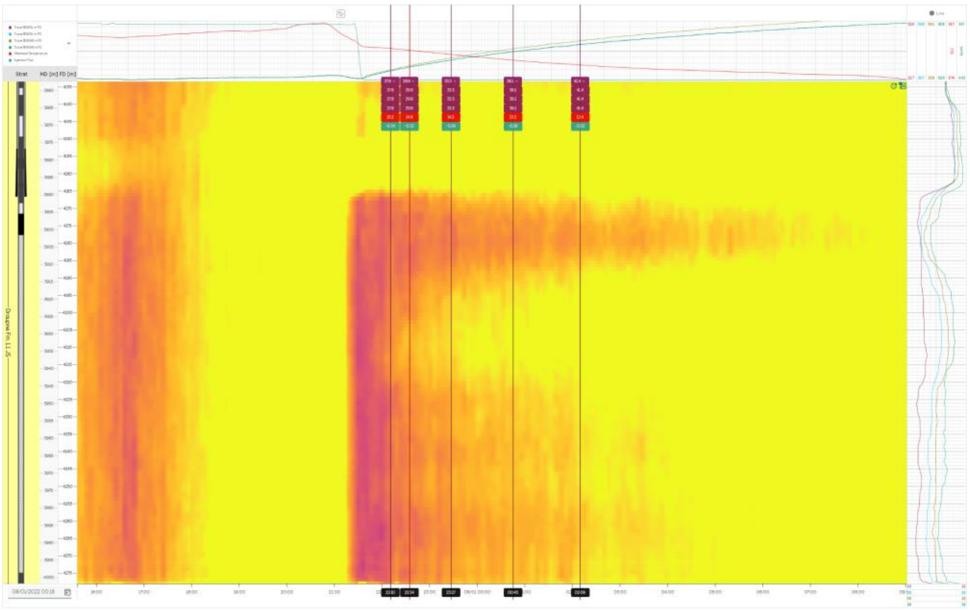
Open

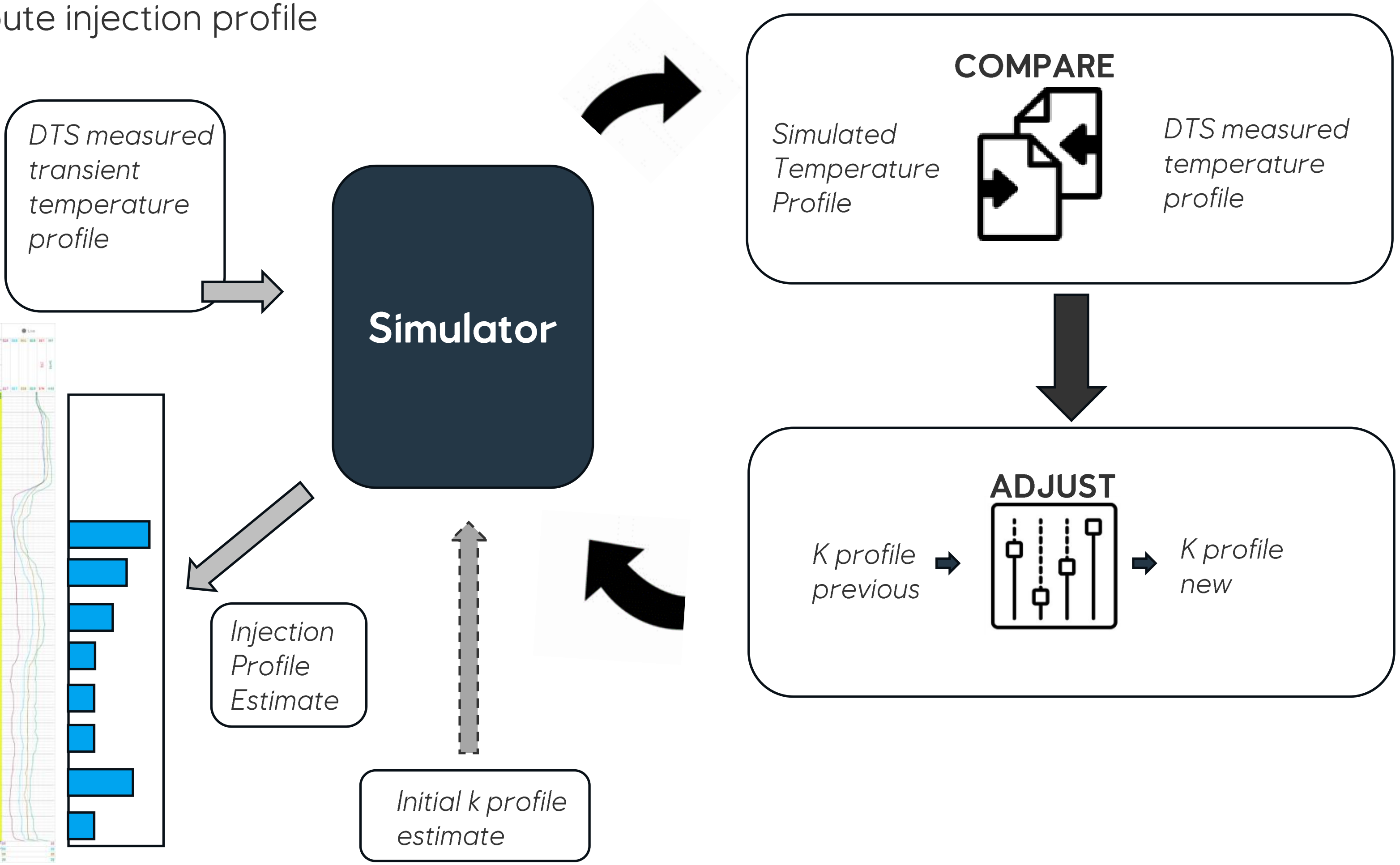
The workflow for injection profile estimation

Invert permeability profile to match simulated transient temperature profile with measured transient temperature profile from DTS -> compute injection profile

fo.tone

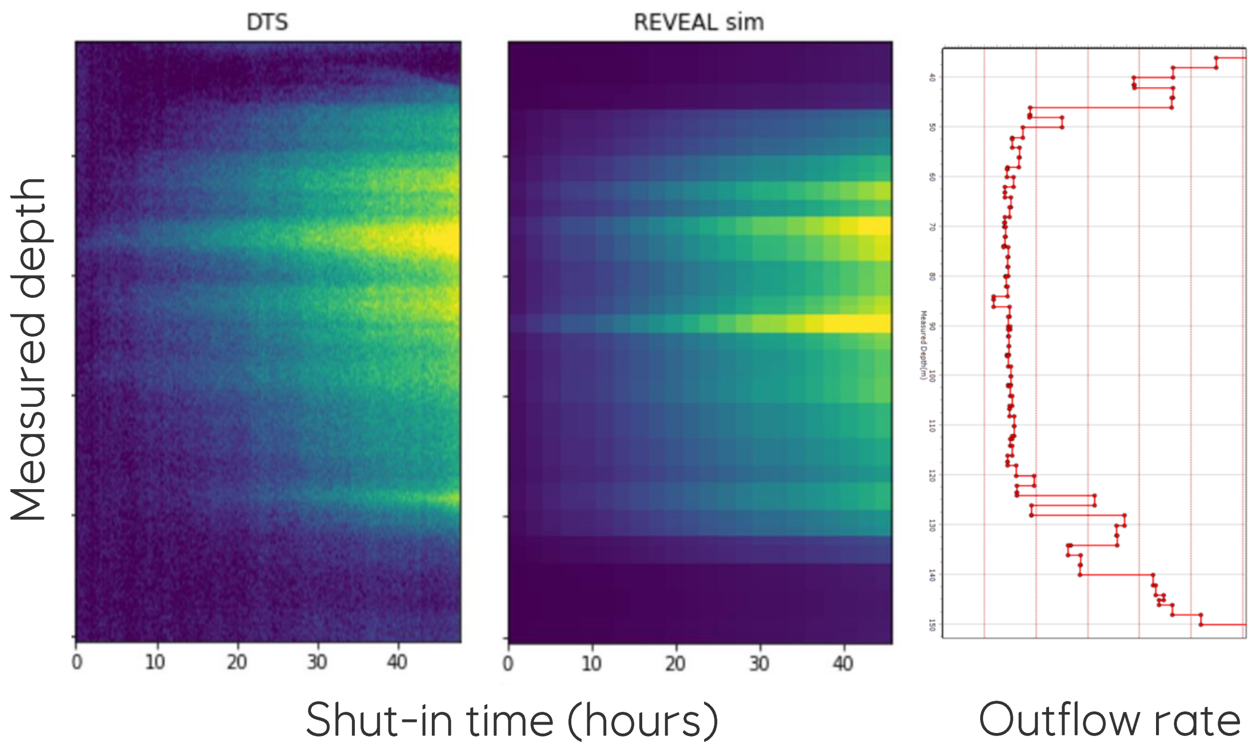
A Johan Sverdrup water injector – DTS temperature measurement visualised in fotone application - First shut in after injection start up



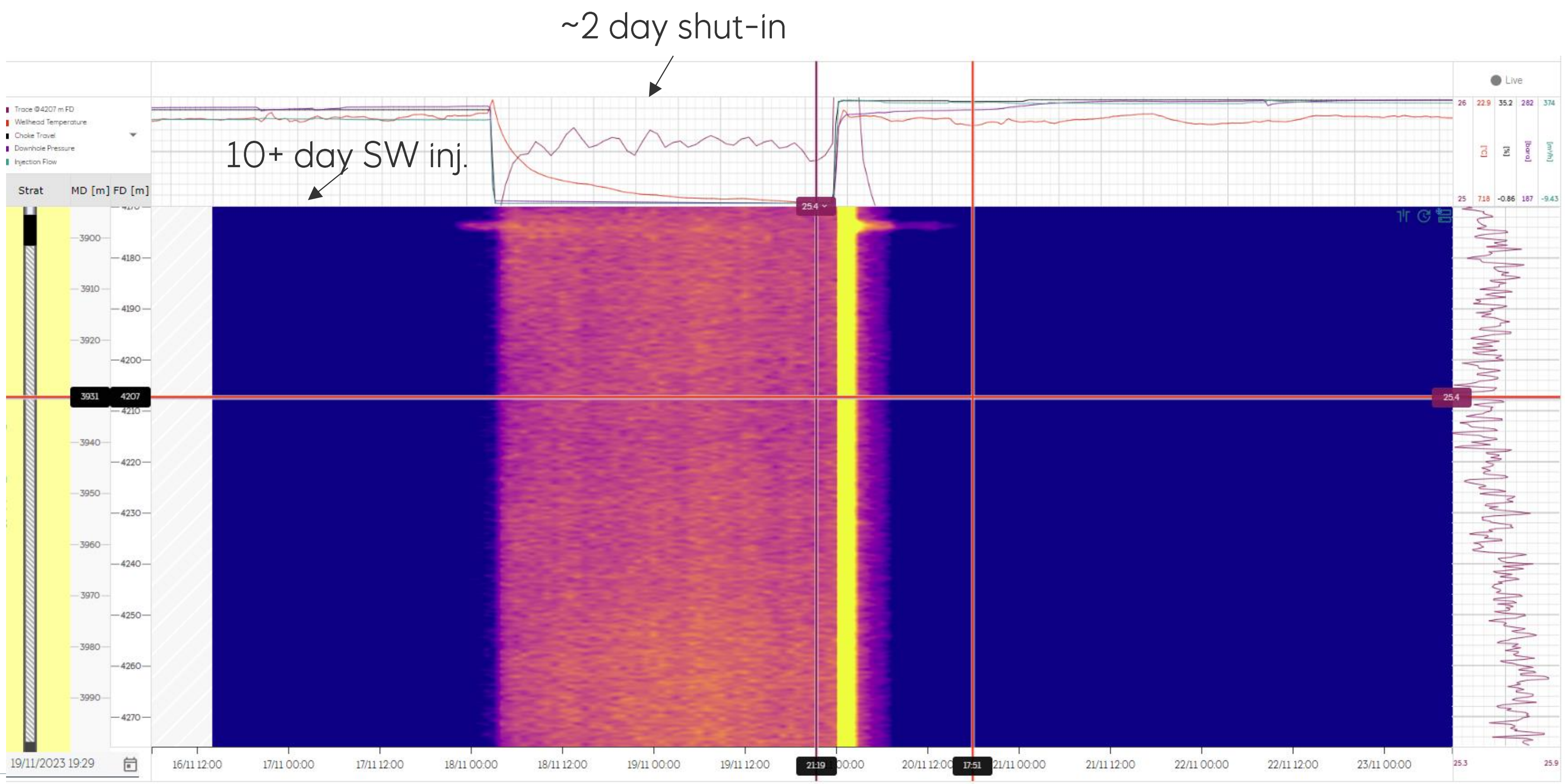


Injection Outflow Profiling: Warm-back analysis for AR-profile

- Numerical simulations with detailed well completion models are used for temperature matching
- Conventional warm-back with shut-in takes too long time after a while
- To avoid long shut-in period, one may consider temperature manipulation (e.g. inject a short period of colder/warmer water before a shut-in)



The issue with using normal shut-in temperature



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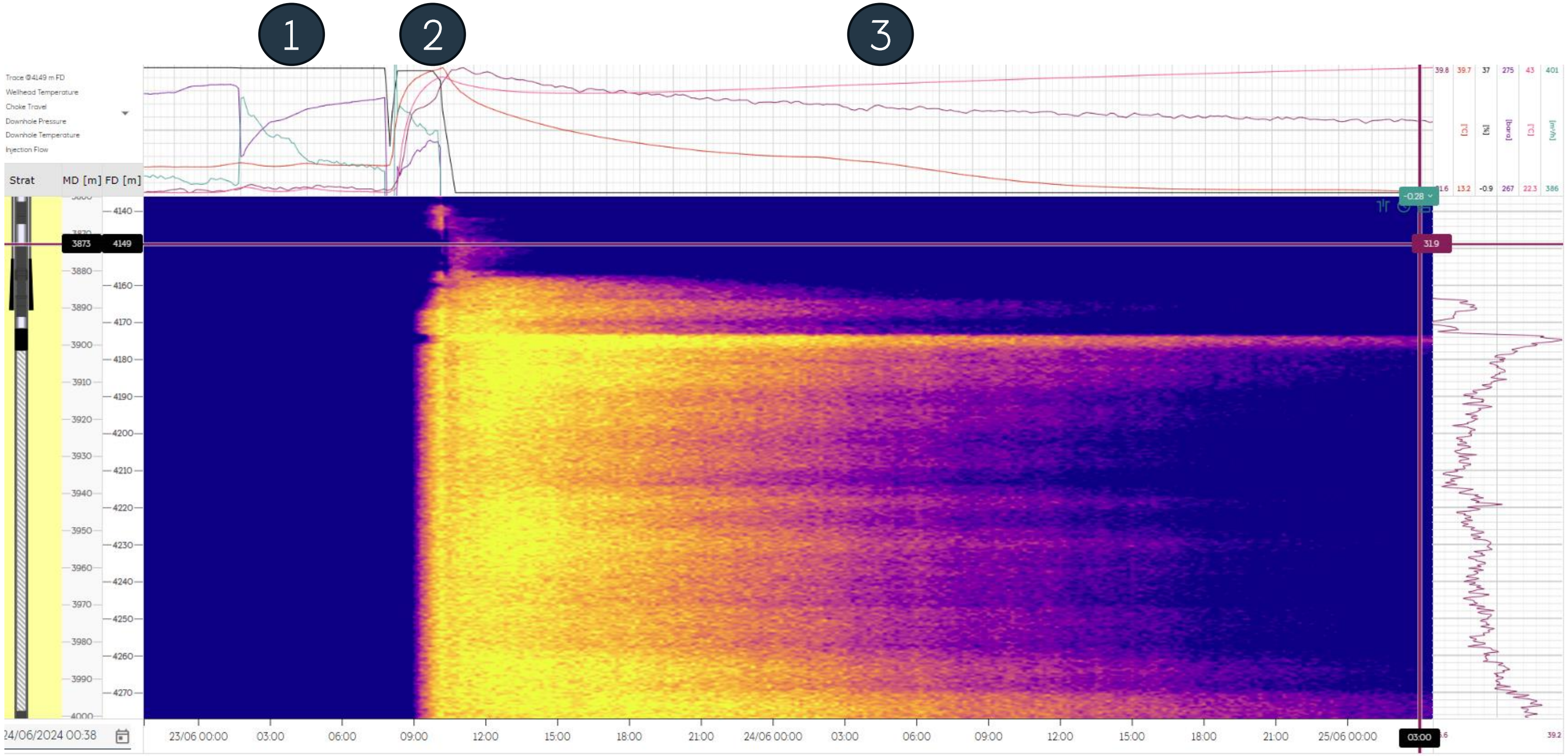
Use short-time injection to trigger a faster warmback

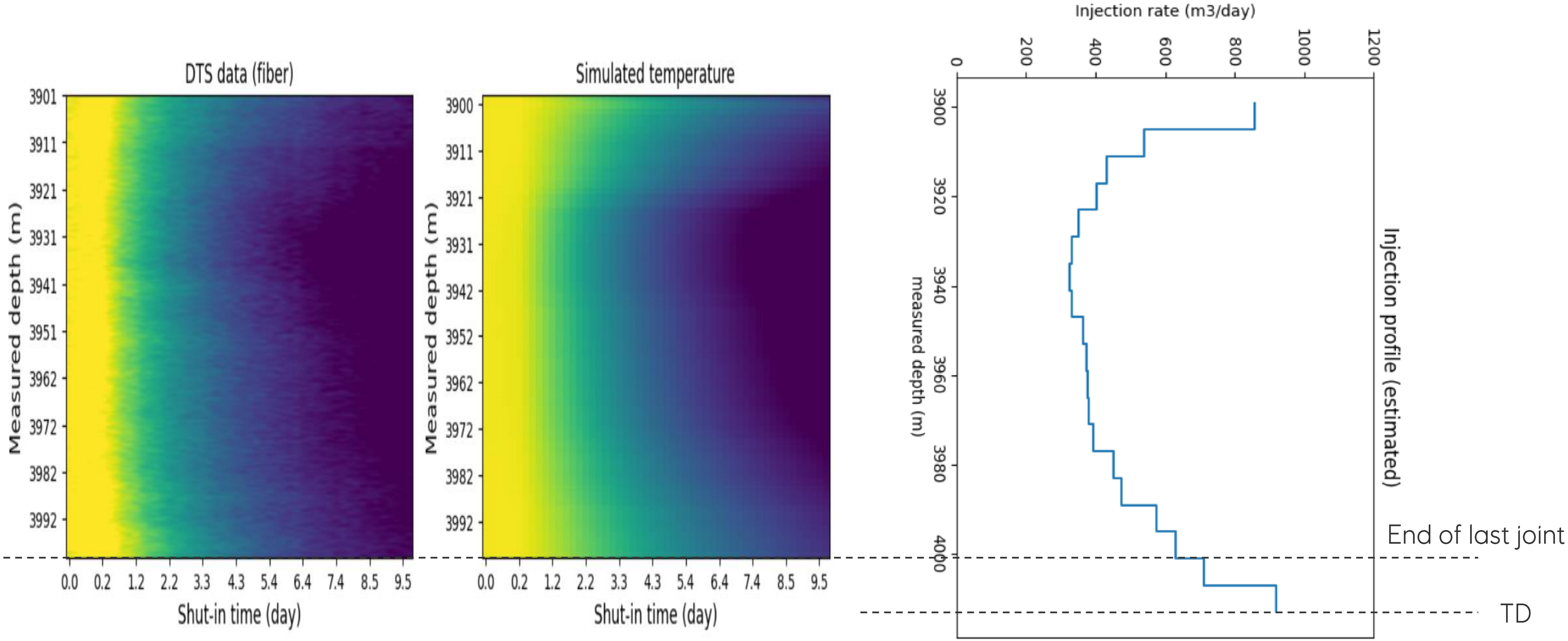


1 ~3-day sea water inj.: WHT ~20 degC

2 ~2-hr prod water inj. WHT 20 => 40 degC

3 10+ day shut-in

Inverted injection profile

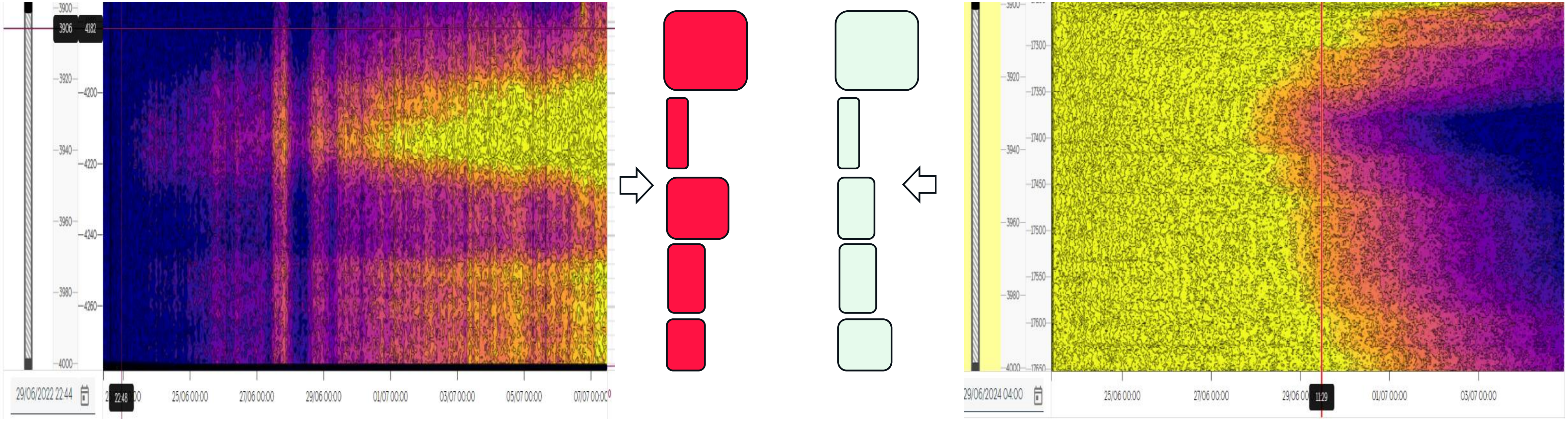


Qualitative checking of changes of the injection profile (1)

Qualitative injection profiles

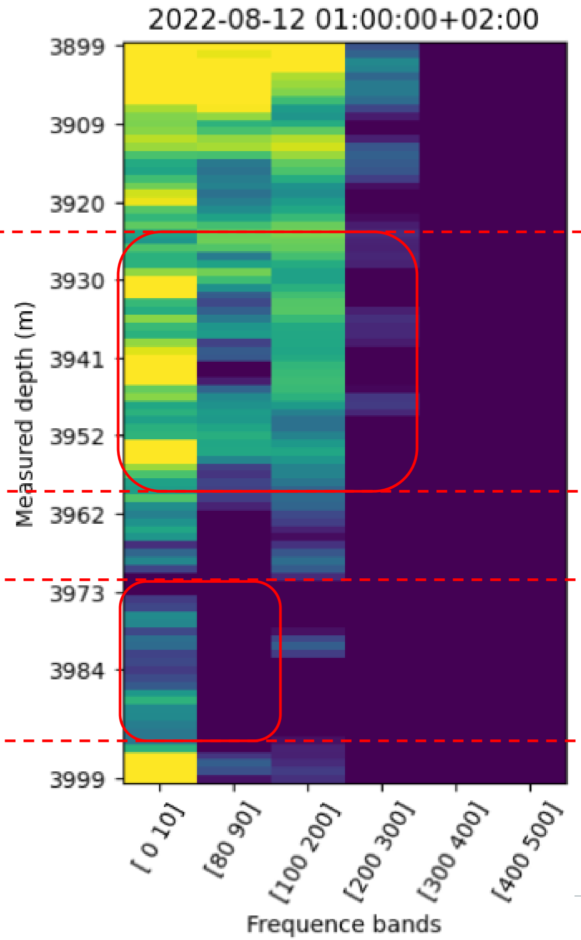
2-week shut-in in 06.2022 (warm-back)

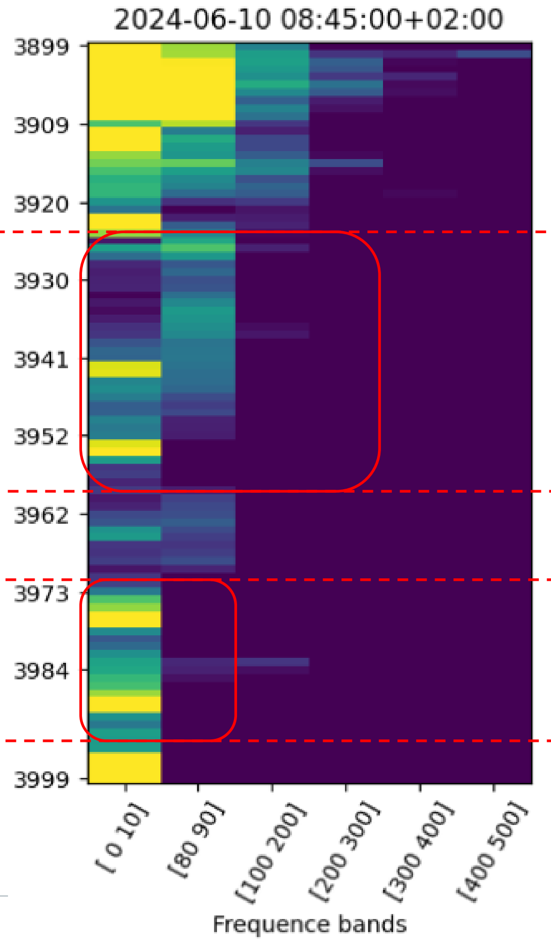
10-day shut-in in 07.2024 (cool-back)



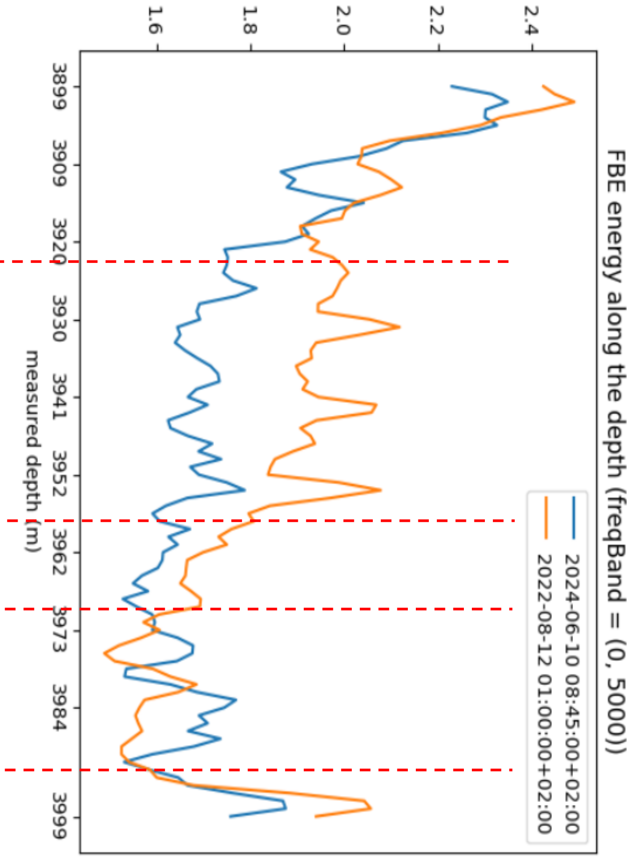
Qualitative checking of changes of the injection profile (with DAS)

Both data are with the same injection rate and in pseudo steady state





- **Mid section**:
  - Acoustic energy (up to ~400Hz) decreases
- **Bottom section**:
  - Acoustic energy (mainly below 100Hz) increases



Other R&D activities

- **Difi Pro Project (phase 1 & 2):**
  - Characterisation of DAS data using experimental data (for specific completion and ICD/AICD types)
  - Mathematical description of physical relations between DAS data and fluid flow through screens or inflow control devices
- **Sand monitoring**
  - Sand production location
  - Sand transport info
  - Max sand-free rate determination
- +++

Concluding remarks

- **Equinor is on its journey of utilizing DFOS in monitoring the reservoir sections of both oil producers and water injectors**. Applications have been developed for
  - Inflow profiling of an oil producer
  - Outflow profiling of a water injector
- **Valuable evaluations/insights have been provided to the assets based on both qualitative and quantitative analysis of the DTS/DAS data**
- **Challenges:**
  - Data-driven modeling with limited ranges of water-cut in the data
  - Noise coming from other sources than inflow/outflow from the reservoirs
  - Model transferring between wells with different types of completions or/and geometries
- **Other applications of DFOS we have investigated (with fibers ended at/above production packers)**
  - Annulus liquid level detection/tracking
  - Hydrate detection/tracking in risers
  - Gas-lift valve leakage detection/evaluation
  - Annulus pressure estimation
  - Safety valve testing
  - Overburden monitoring

Acknowledgement

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