

Cost-effective and Sustainable Water Injection with the X-flow Concept

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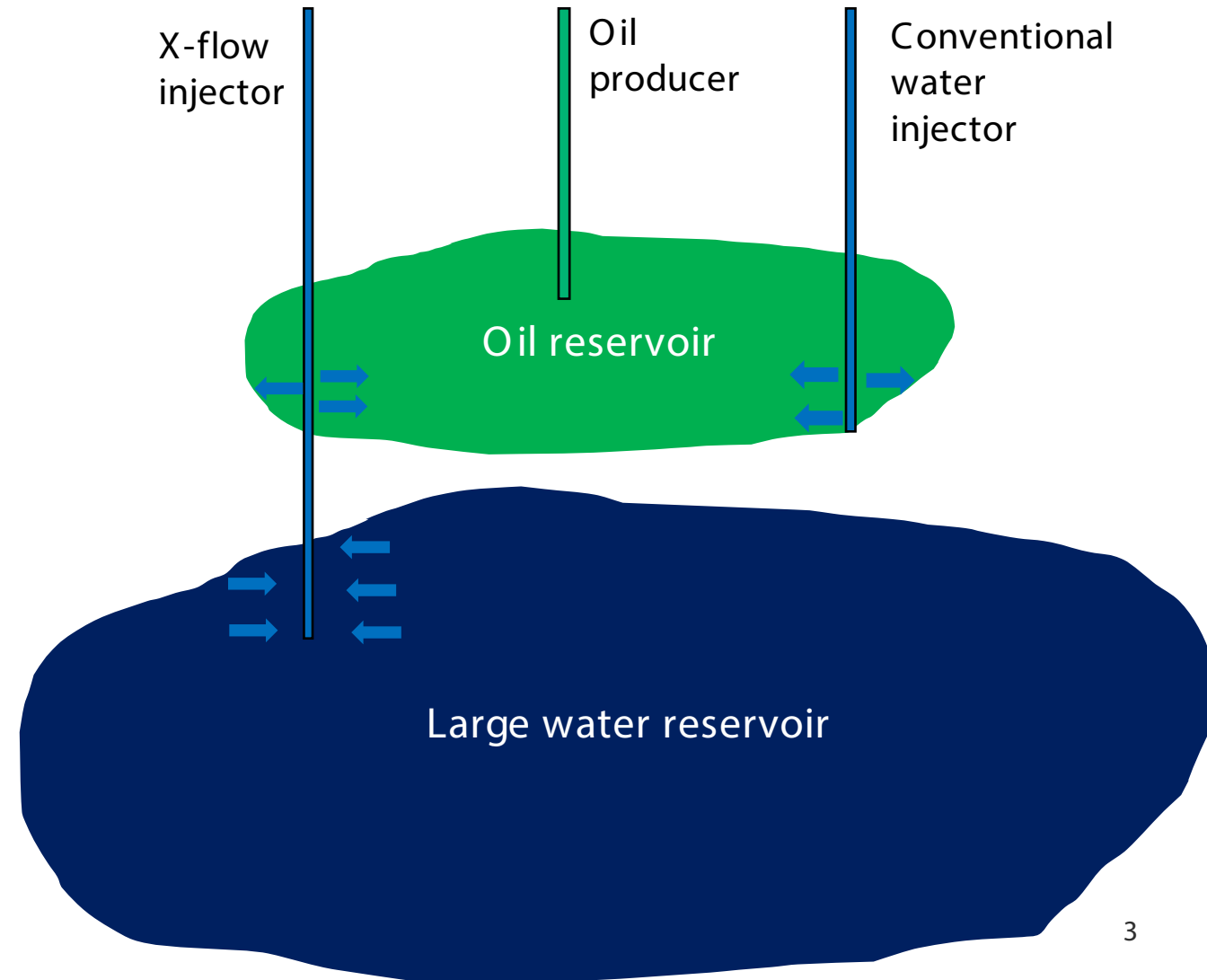
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Introduction

Water injection via x-flow

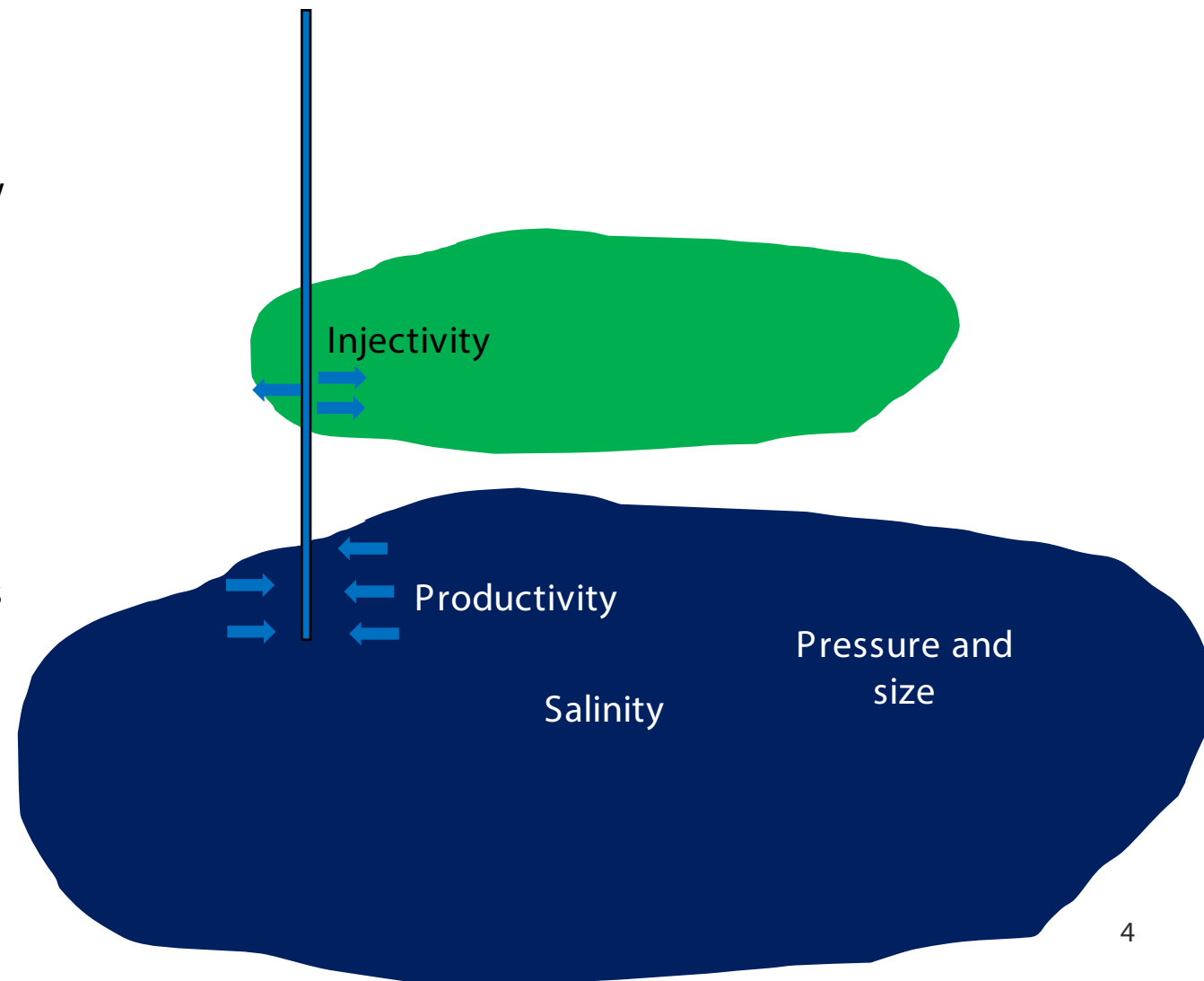
- Some oil reservoirs require extra pressure support
- Normal concept: Water injector with topside pump, treatment of water, subsea pipeline if needed
- X-flow concept: A well short-cutting two zones or reservoirs
 - Flow of formation water
 - Normally no chemical treatment of water
 - Can be assisted by ESP or not



Requirements for the concept

.. based on published experience

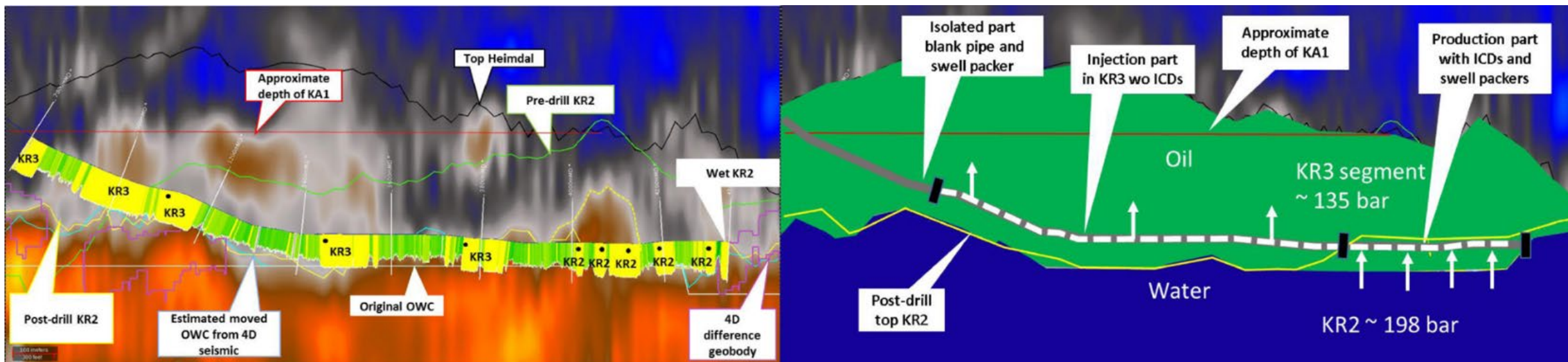
1. Sufficient injectivity in the receiving reservoir or zone
2. Adequate productivity in the source reservoir or zone
3. Chemical compatibility of the injected water, with low or negligible scaling potential
4. A sufficient and sustainable pressure differential between the source and receiving intervals
 - or the availability of power assisted flow (e.g. ESP)
5. Absence of particulate transport that may impair injectivity
 - or the availability of effective mitigation measures such as fracturing or back flush capability



Alvheim x-flow water injector

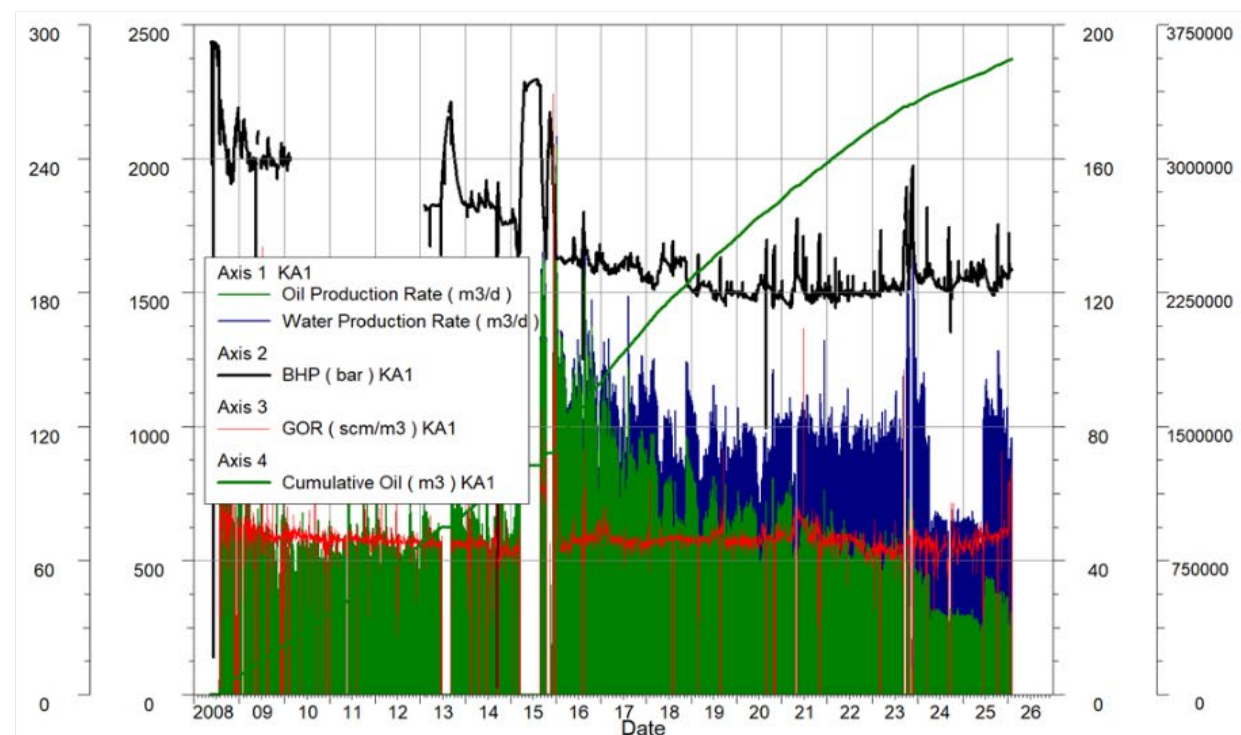
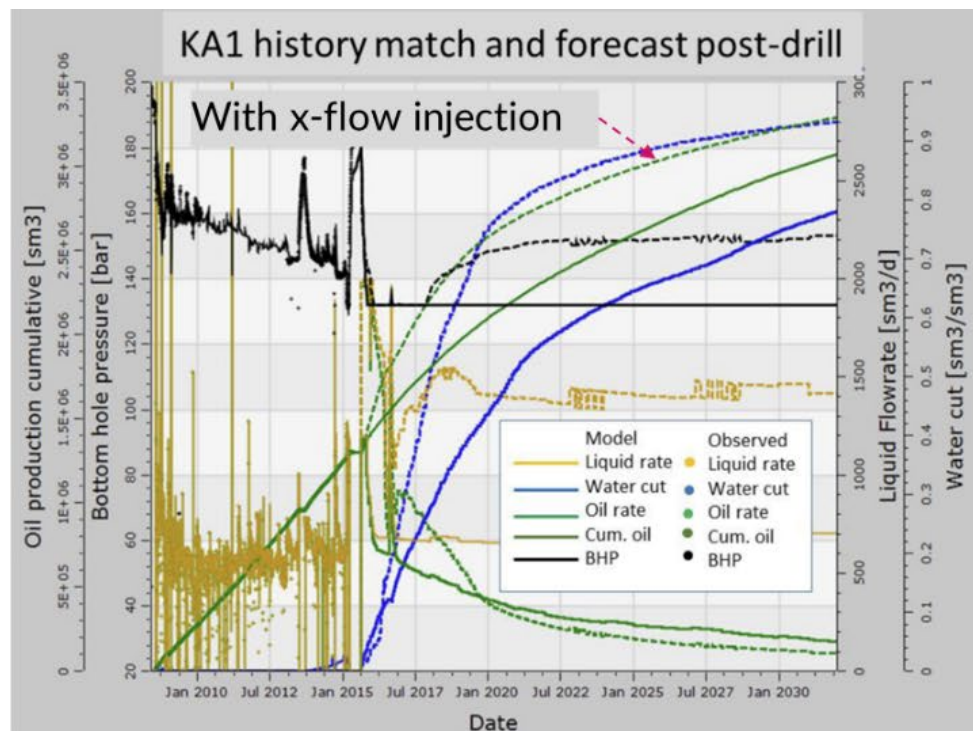
Langaas et al. (2016)

- Well planned as producer into the lower zone of the Heimdal formation at the Kneler accumulation
 - Oil found, but mainly in the upper zone that already had an active producer
 - Upper zone at low pressure (~65 bar lower pressure vs lower zone)
- Within 24 hours, well was redesigned from producer to x-flow based injector
 - Existing dynamic model were used pragmatically in the design process



Forecast vs. Actual

- Design objective was to enhance pressure support to the upper zone and old well KA1
 - At same time continue keep KA1 close to bubblepoint pressure (130 bar) to safeguard oil reserves
 - Maintain natural influx (unknown if oil or water)
 - Keep option for late life pressure blow down

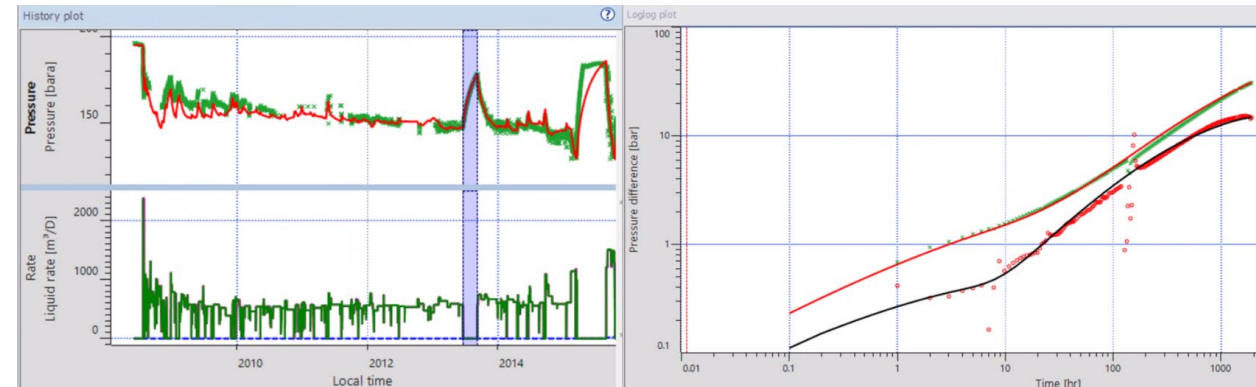


Analysis

Analytical modelling of KA1 and upper zone segment

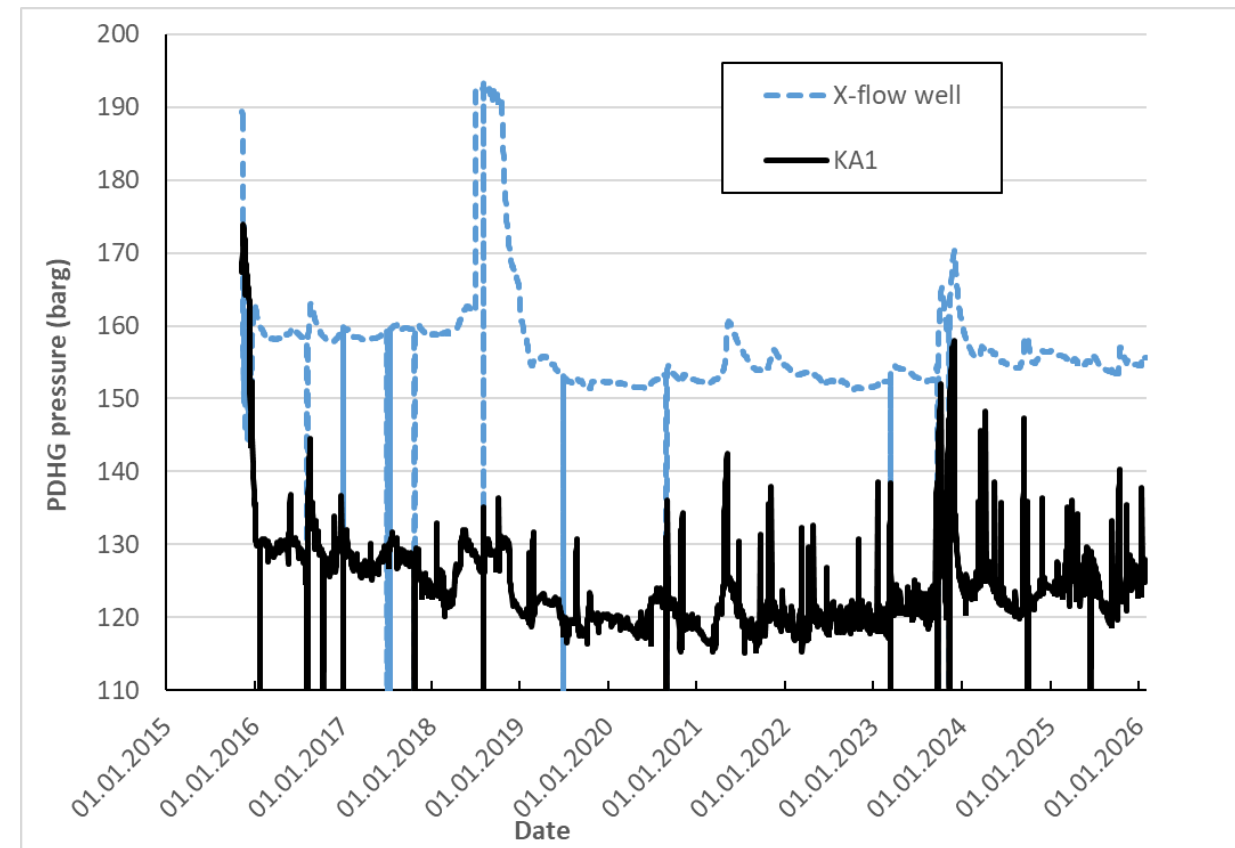
- Cylindrical composite reservoir model, with KA1 represented as a vertical well at the centre
- A boundary of reduced transmissibility was imposed at a radius of 400 m, surrounded by an infinite-acting reservoir
- Good global and local match (PBU 2013), matching the natural influx to the segment
- Onset of x-flow December 2015
 - Mismatch ~ 25 bar
 - Can derive that x-flow based influx is 38% of the natural influx
 - Design objective was closer to 100%

$$F_n \Delta p + F_x \Delta p \approx F_n (\Delta p + 25 \text{ bar})$$



Alvheim x-flow well: Key learning

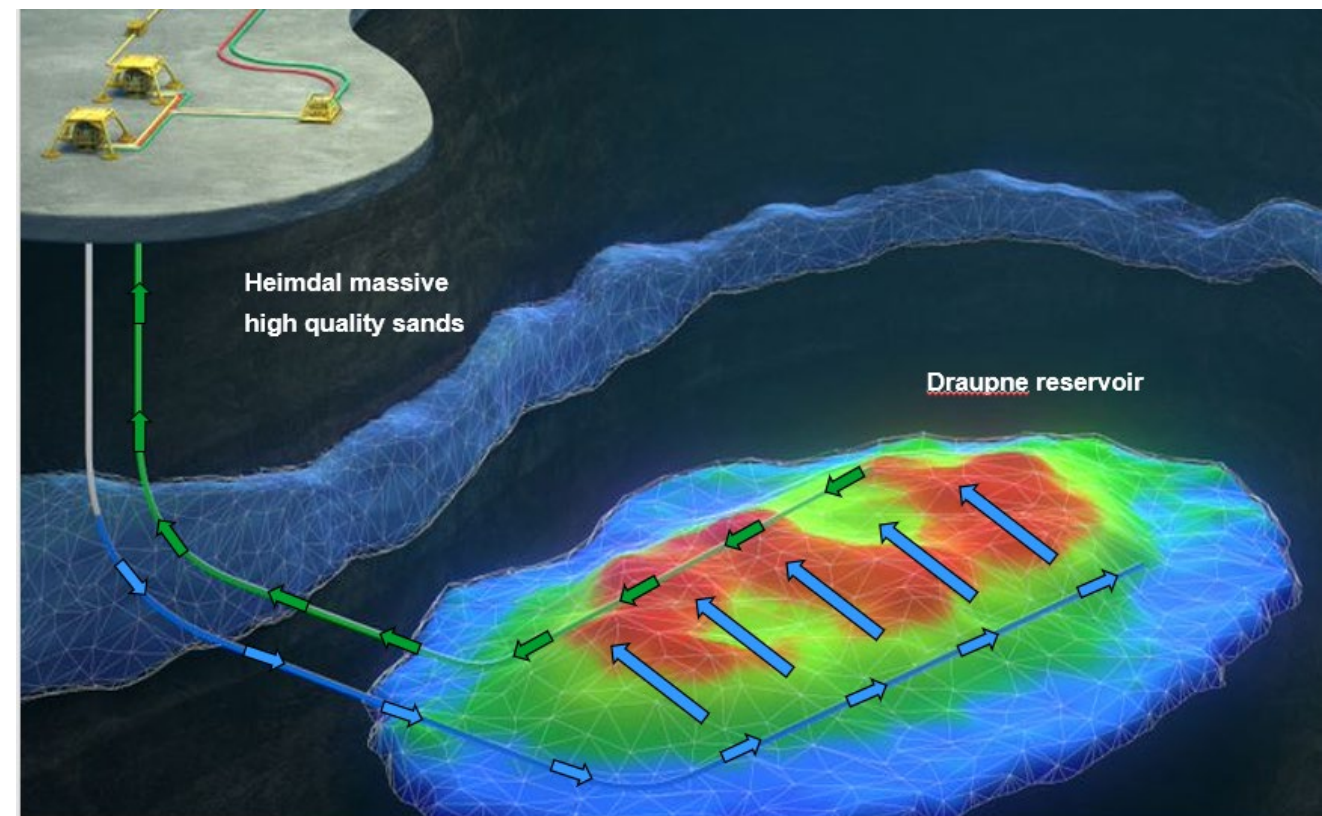
- Excellent planning and execution of the clean-up, secured clean production and injection zones
- Productivity (of the Heimdal lower zone) much less vs. the reservoir model
 - Effective permeability much less than near-well permeability
 - 2018: Likely annulus sand collapse of the production interval, causing temporary plugging. This reduced the productivity further
- More ideal well design?
 - Use a longer production interval
 - Use flow control valve to control x-flow
- Injectivity have been stable for 10 years
- Huge value: Have helped accelerate KA1 oil while securing long term reserves
 - KA1 have produced 14 mmbbl of oil 2016-2025, much more than forecasted



Hanz x-flow injector

Design

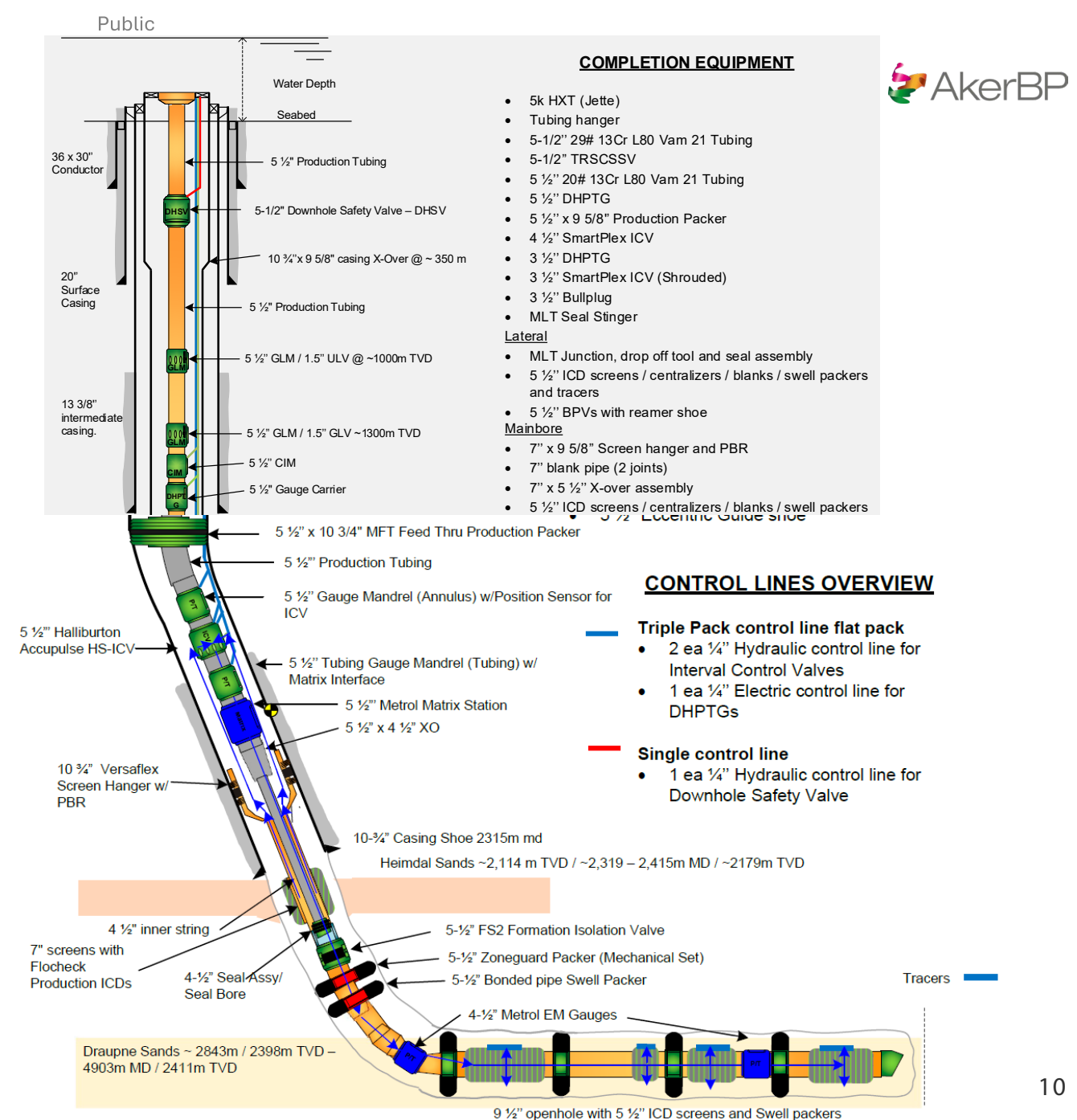
- X-flow injector concept possible
 - Massive Heimdal formation reservoir above Hanz
 - Proved as good aquifer with good productivity
 - Draupne thinner sands have excellent permeability
 - Both Draupne and Heimdal at ~ hydrostatic pressure
 - Compatible formation water
- X-flow concept carefully reviewed, excellent challenge/support by the Hanz partners
- Robust plan
 - Line drive with horizontal injector
 - FCV across Heimdal
 - Extensive clean-up period and monitoring, before start of x-flow



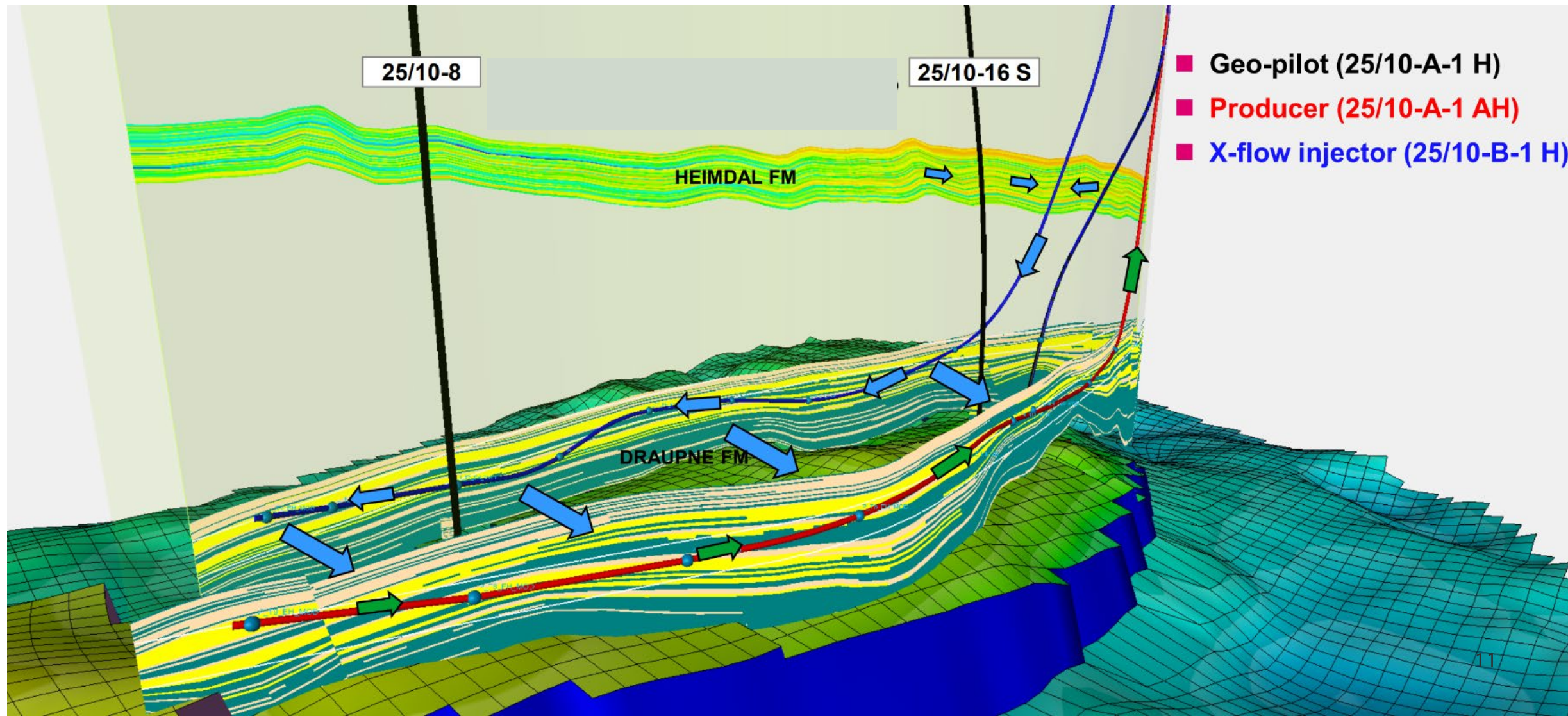
Hanz

Well design

- X-flow concept first planned as lateral branch of producer
 - To reduce project cost
 - Had no FCV to control x-flow rate
- Risk review ended in making a dedicated x-flow well
 - FCV that could control x-flow rate
 - Wireless gauges in lower completion to assist well surveillance and help estimate rate

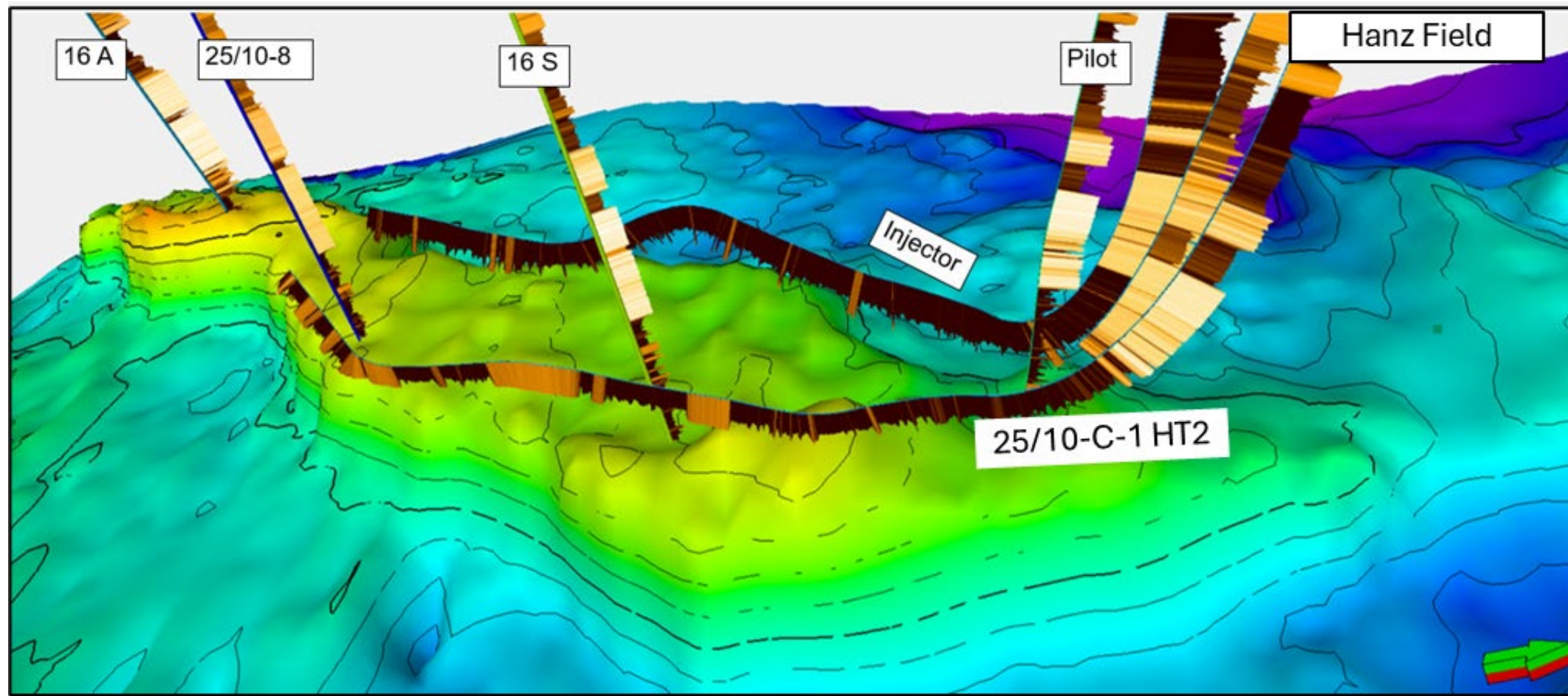


Heimdal and Draupne expectations...



..vs drilling result

Heimdal as prognosed, Draupne quite different



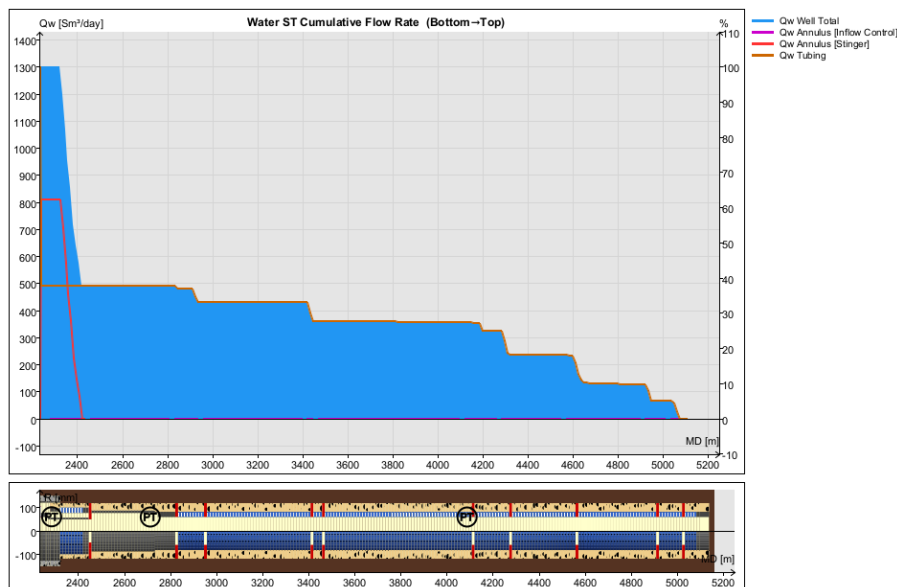
B-01 vs C-01 pressure

- Low degree of communication between injector and producer
- X-flow well work as per plan, with quite similar productivity and injectivity

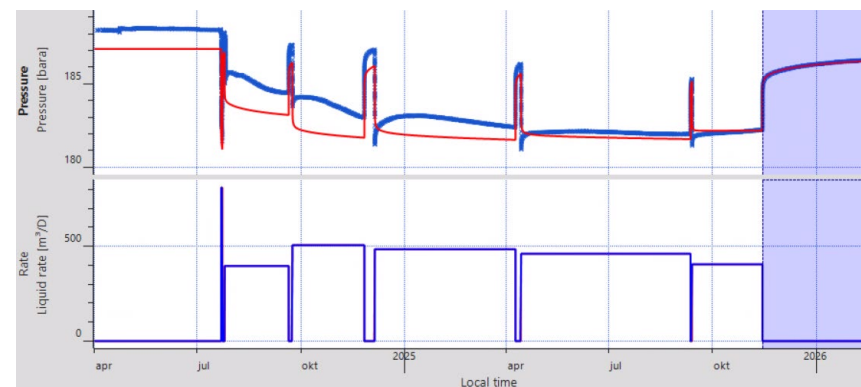
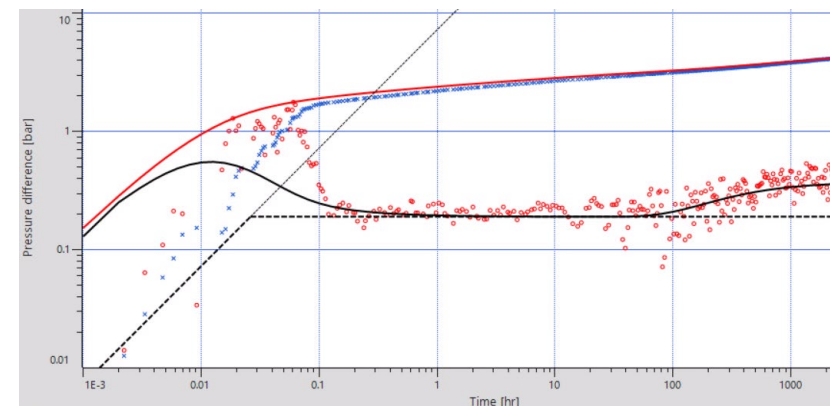


Analysis x-flow well

- Best rate data is from clean-up
 - Clean up of Draupne alone
 - Clean up of Heimdal, commingled flow w Draupne
 - History match all data with a steady state inflow model with all lower completion details
 - Heimdal PI $\sim 150 \text{ Sm}^3/(\text{d} \cdot \text{bar})$
- lower than expected

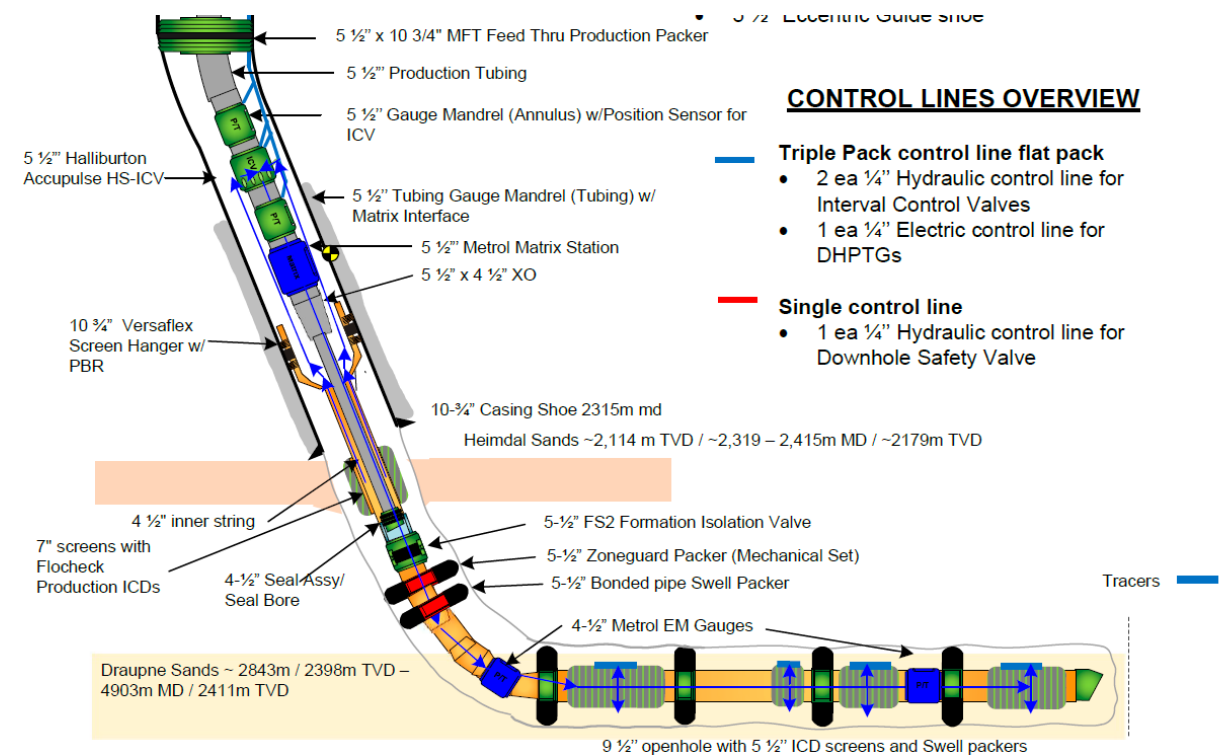


- Heimdal PTA indicate an effective permeability $\sim 115 \text{ mD}$
 - Much less than expected, but within uncertainty range when including analogues



Hanz x-flow: Key learning

- Well design with Heimdal FCV secured good clean-up and has also been used recently to close the x-flow
 - Another FCV on Draupne would have made the clean-up planning more flexible
- Draupne reservoir was very different than expected, and is the main reason for the lower than planned water injection
- Heimdal effective permeability also lower than our models, but similar scenarios seen on some Heimdal analogues
 - Would have been a limitation for water injection if Draupne was closer to expectation
- A more standard water injector would likely not have done a better job, and would have increased cost and environmental footprint (subsea pipeline, pumps, water cleaning)



Conclusions

- X-flow based water injection is a cost-effective and sustainable alternative given some requirements
- Many global examples, where the GoA example is the best documented and a huge success story
- Two pilot projects done on the NCS
 - Alvheim Kneler
 - Well re-planned in 24 h, no option for FCV that would have strengthen the robustness
 - Effective permeability Heimdal (lower zone) lower than expected
 - Low cost and huge value
 - Hanz
 - Robust well plan building on the Alvheim pilot, trusting Heimdal as a source reservoir
 - X-flow well has worked as planned
 - Water injection rate much lower than design
 - Draupne reservoir very different vs. expectations
 - Heimdal effective permeability also lower than expected
 - Concept saved cost and emissions vs. a standard solution with subsea pipeline
- Concept is looked at for a new ongoing field development



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