Snøhvit CO_2 storage project: Understanding the role of injection induced mechanical deformation

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Lawrence Livermore National Laboratory

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Program Goal No. 4

- "Develop Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation."

Benefit Statement

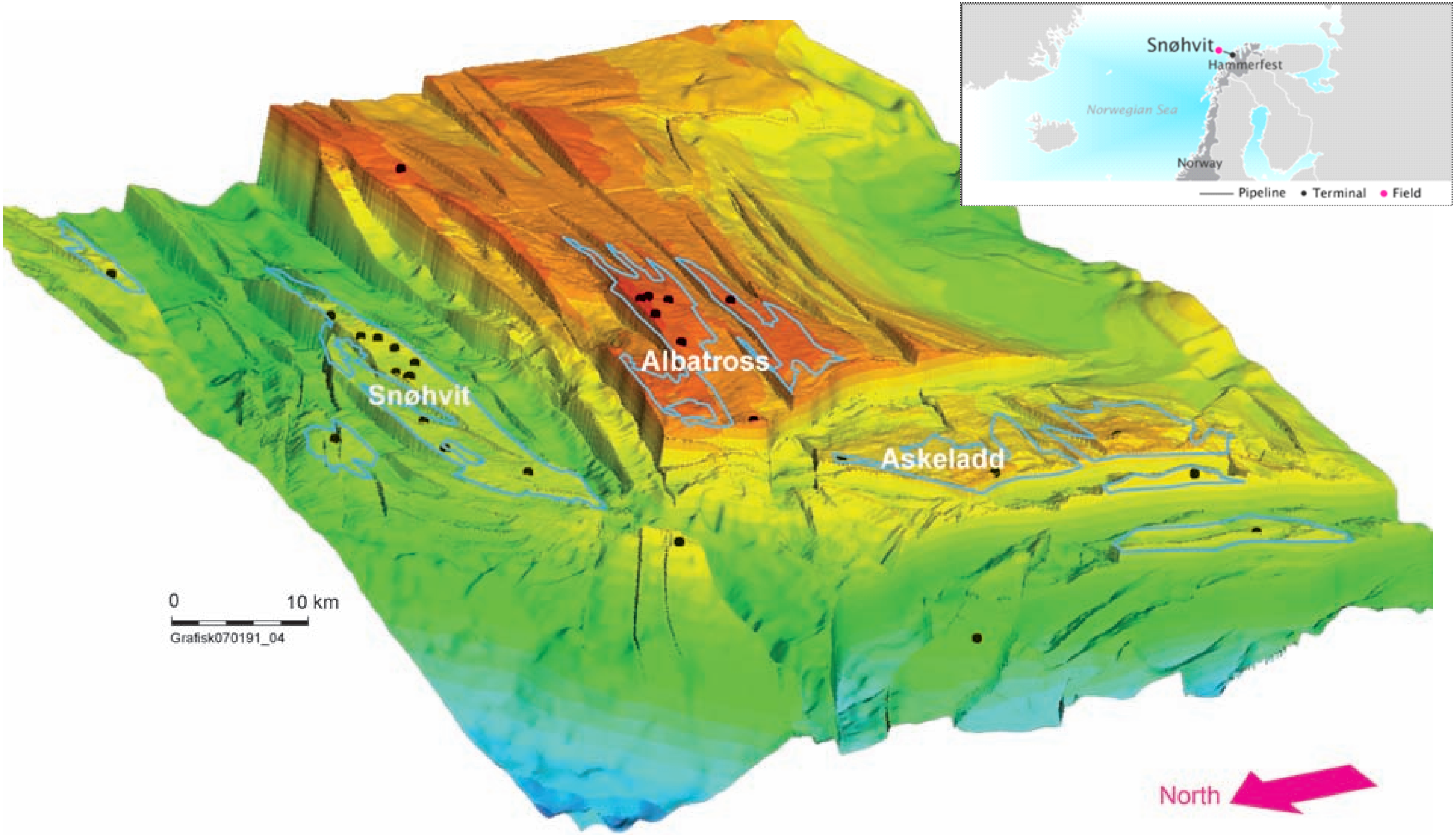
- An understanding of hydromechanical interactions is essential for effective monitoring and prediction of reservoir performance. This is especially true for storage systems expected to experience higher overpressure.

- This project has developed new analysis methodologies for:

  - probabilistic assessment of fault reactivation potential and in situ stress sensitivity

  - dynamic well-test analyses using multi-rate gauge data

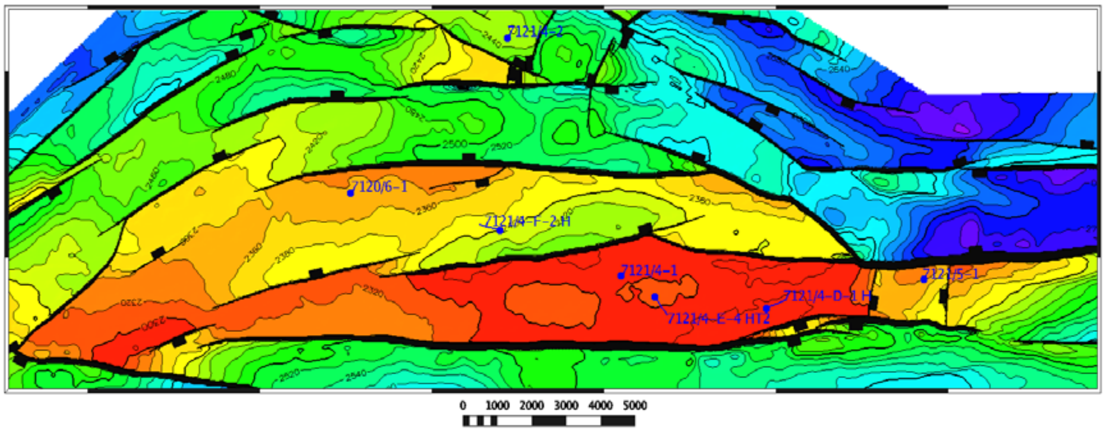
Snøhvit

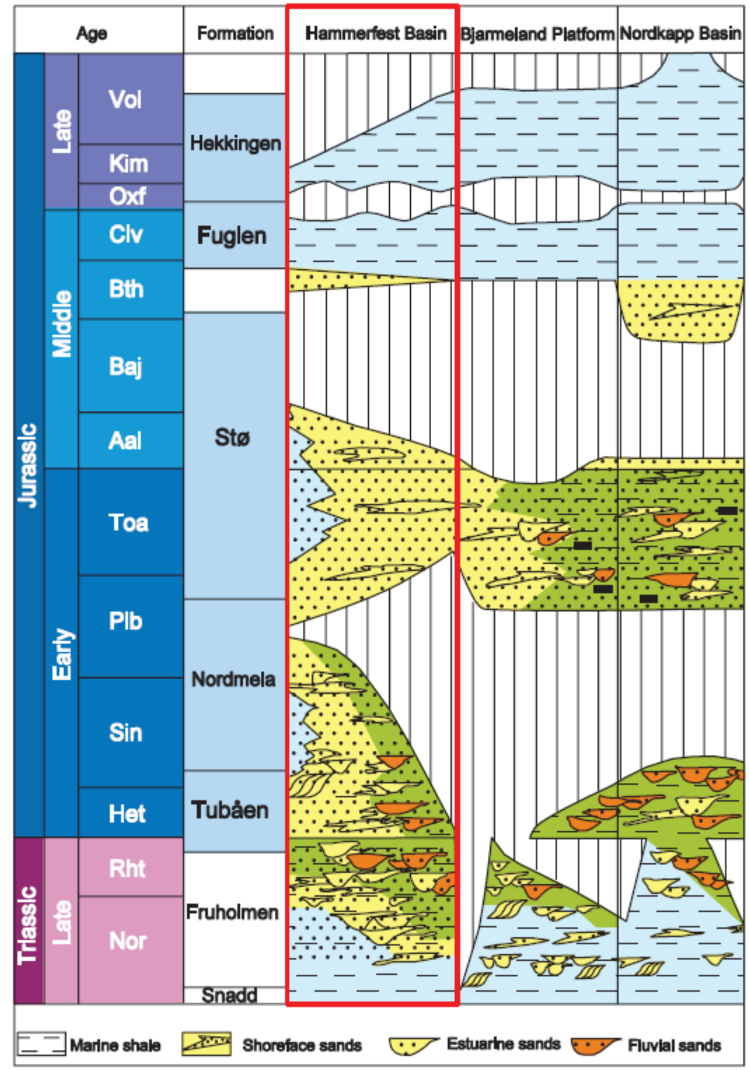


Structural diagram of Hammerfest Basin at Middle Jurassic level (approx. age of producing reservoir). Blue lines outline the gas fields [from Spencer et al., 2008].

Snøhvit

Depth map at top of Fuglen Fm. (below) and stratigraphic section (right) [from Wennberg et al., 2008]





- Producing natural gas with 5-8% CO_2 content, which needs to be reduced before liquefication.
- Separated CO_2 was originally re-injected into Tubåen Fm. at approx. 2400-2600m depth.
- Injection began in 2008, but in 2010 Statoil announced storage capacity in Tubåen was lower than expected. Operators recompleted well and have continued injection in the shallower Stø formation.

Focus areas where modeling can help monitoring and project management:

① **Decision-based Modeling**

- Using modeling to inform instrument design and deployment schemes

② **Data Integration and Data Assimilation**

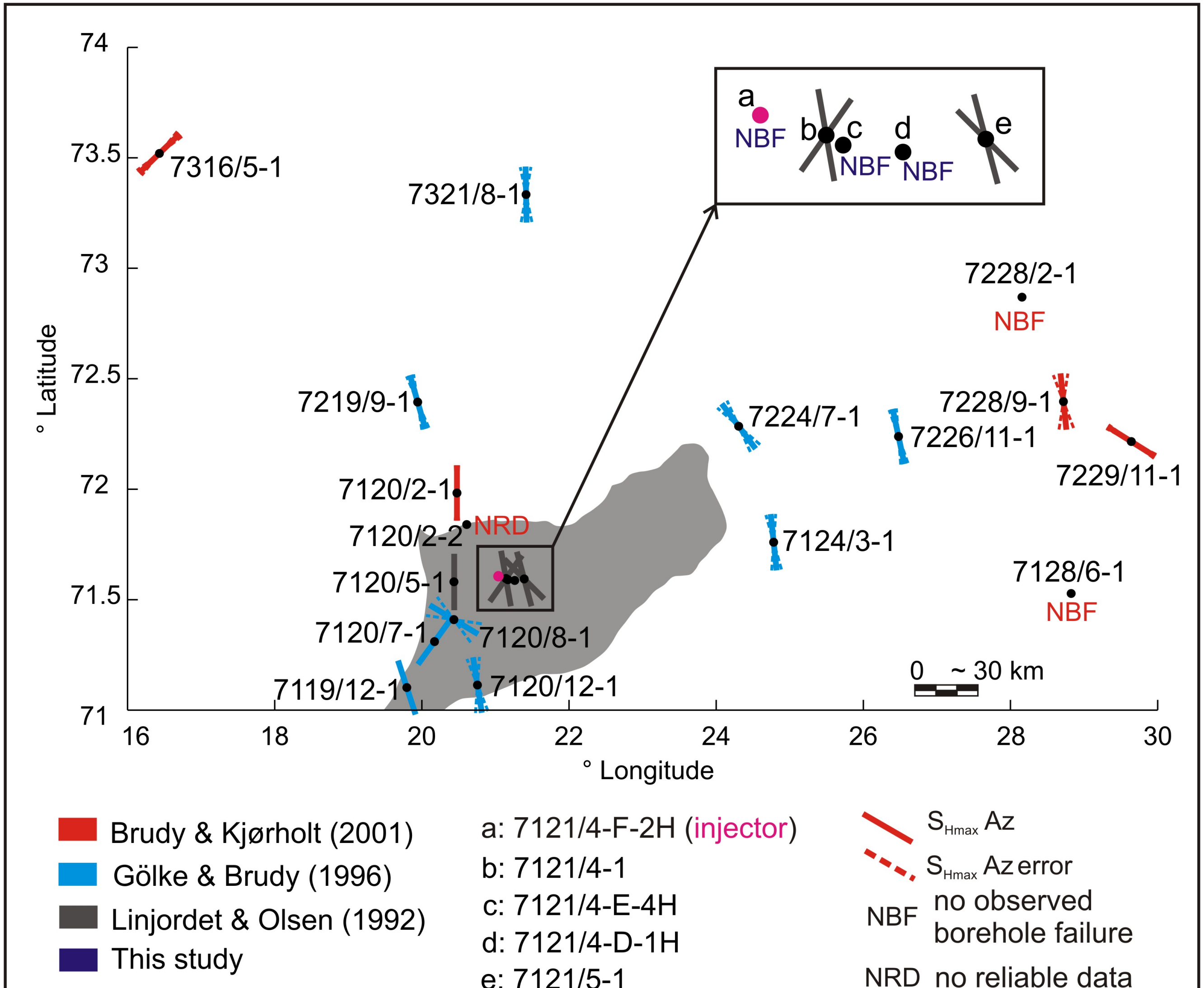
- Merge diverse monitoring data sets into unified interpretations
- Deterministic or stochastic inversion of monitoring data

③ **Uncertainty Quantification and Risk Assessment**

- Quantify how uncertainty impacts performance and risk

Snøhvit Case Study 1

Using modeling to address uncertainty in stress measurements



[Chiaramonte et al. 2014]

A key project concern was whether excess fluid pressure could reactivate faults and create leakage paths

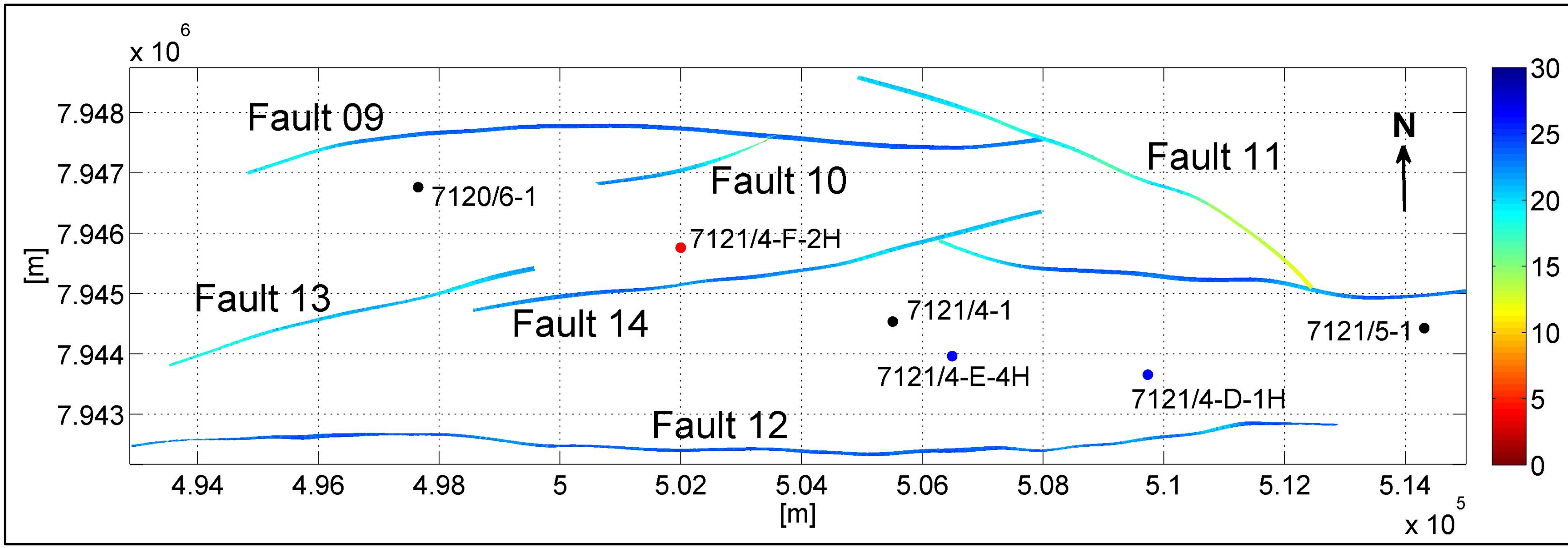


Figure: Model prediction of excess pressure (MPa) necessary to initiate fault slip with the base case scenario parameters, which corresponds to a SS/NF environment with N-S S_{Hmax} direction.

Sensitivity analyses reveal that critical uncertainty is SHmax orientation, but overall leakage risk is low

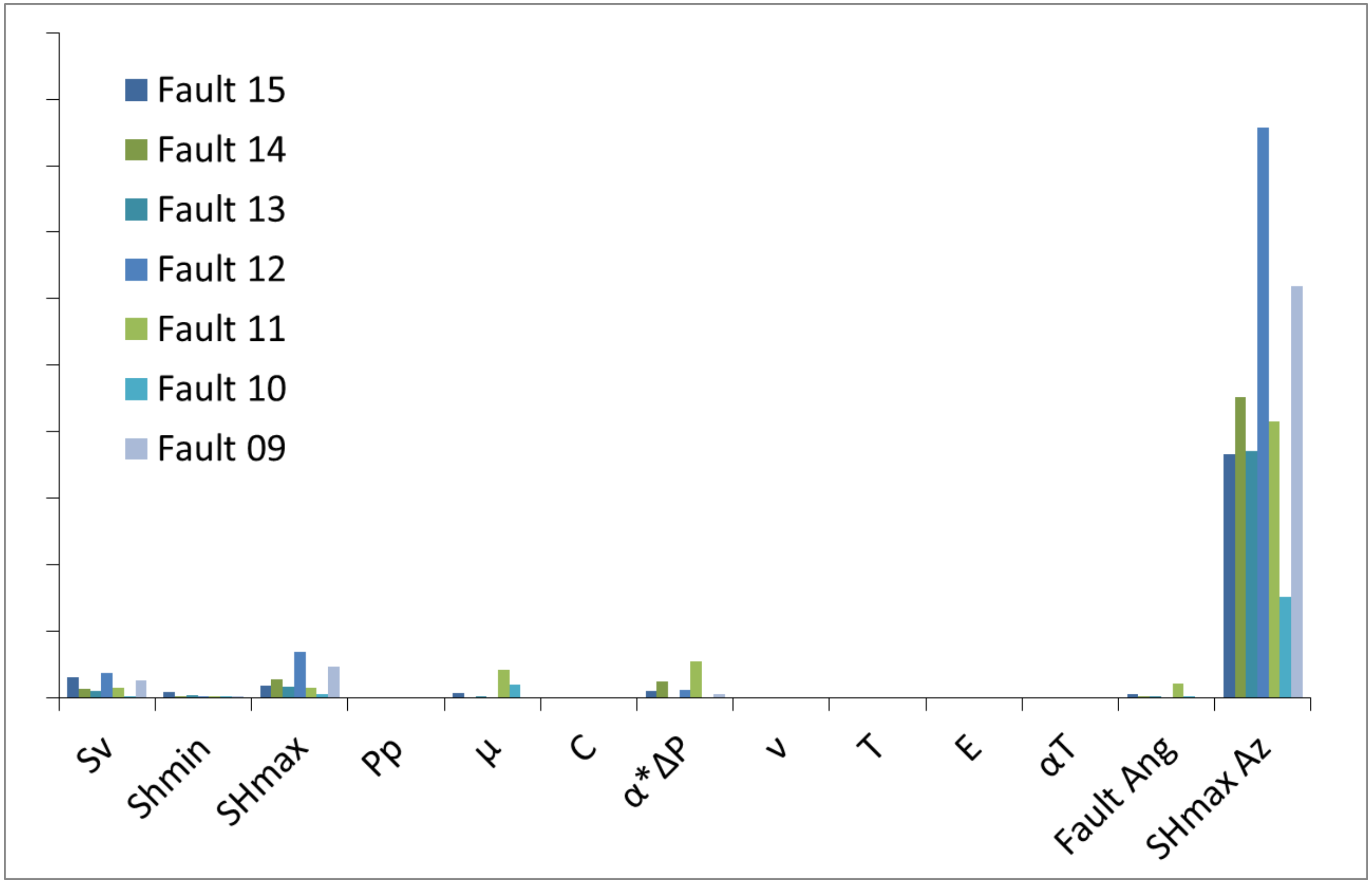


Figure: SHmax azimuth dominates critical pressure sensitivity

- Suggests highest-value target for future characterization efforts

Snøhvit Case Study 2

Welltest analysis and continuous inversion of gauge data

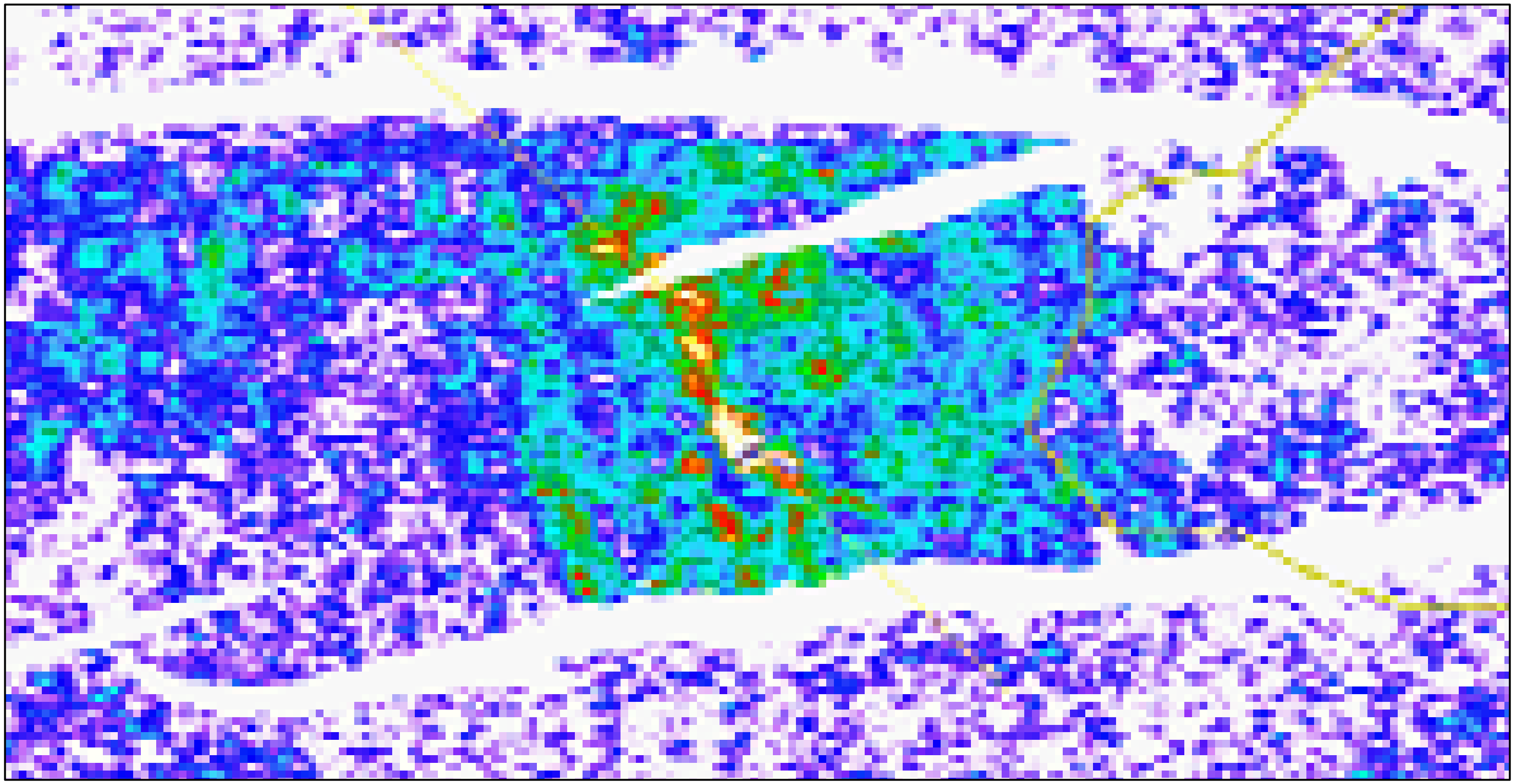
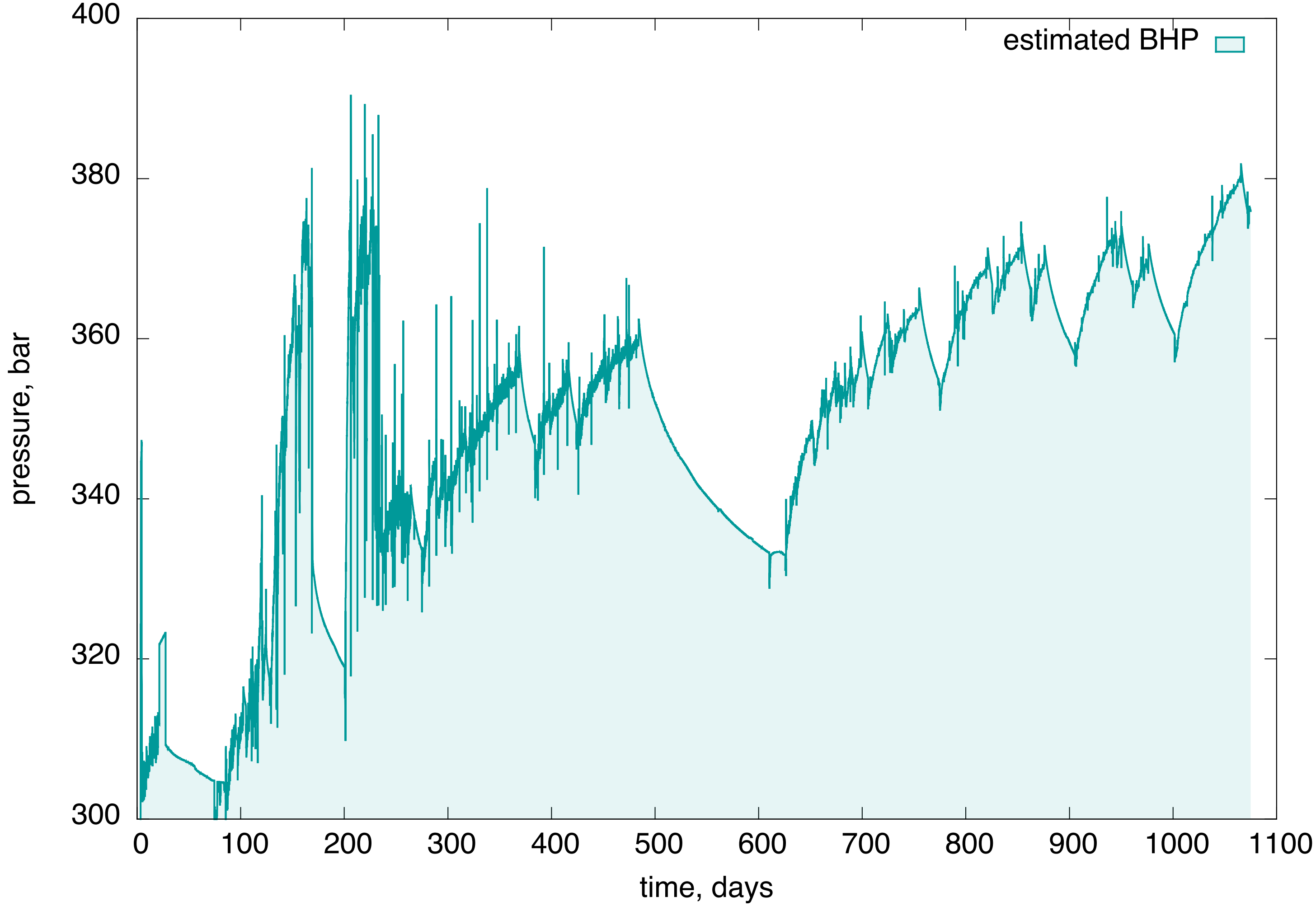


Figure: 4D difference amplitude maps, 2003-2009, lower perforation.

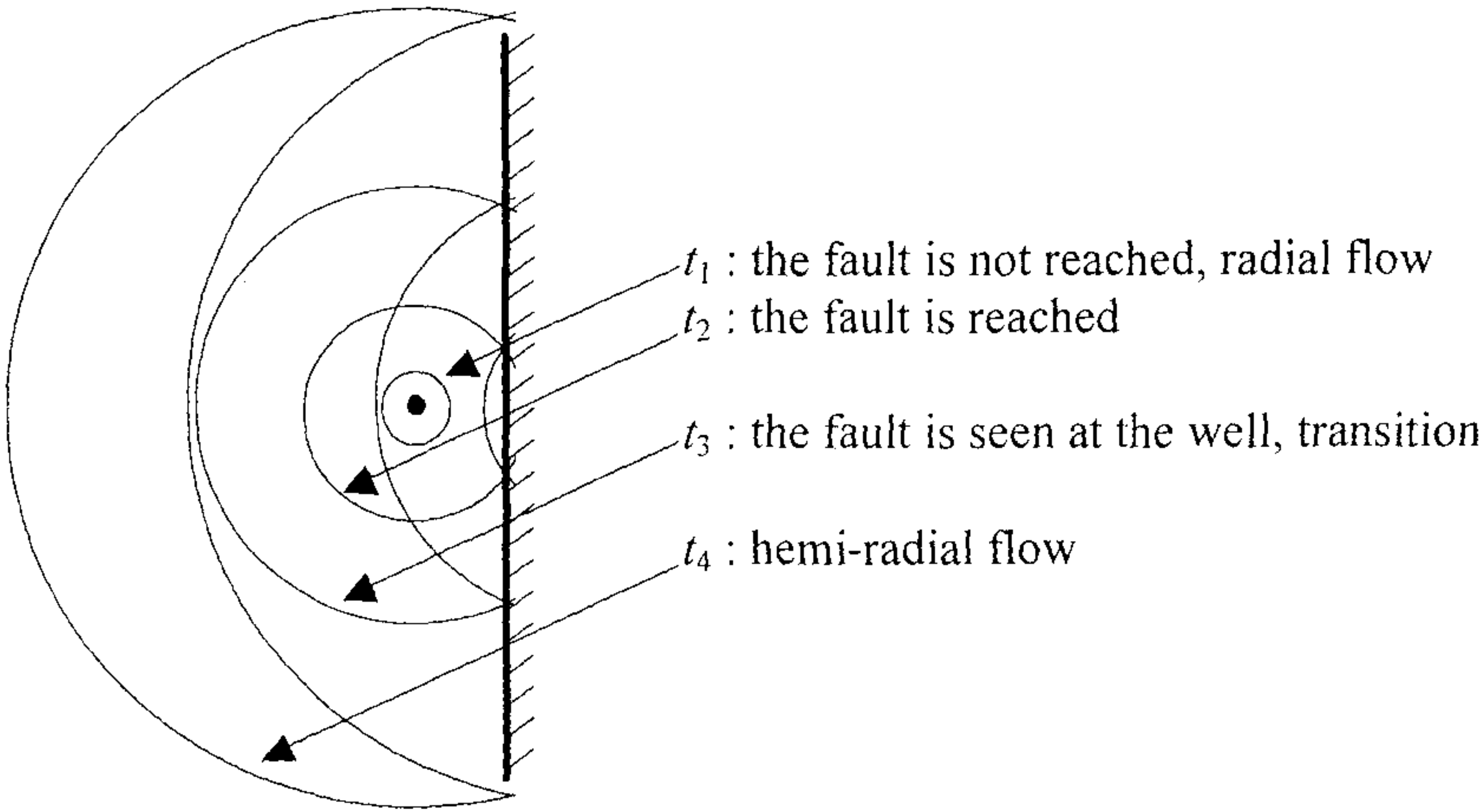
(Hansen et al. 2012)

Pressure response indicative of a partially compartmentalized system



BHP estimated from permanent pressure/temperature sensors at 1782 mTVDss, hourly data.

Well tests commonly used to look for flow barriers and other indications of reservoir structure



[Figure from **Bourdet, 2002**]

Falloff analysis showed clear indications of flow barriers

- Results suggested flow barriers at 110, 110, and 3000m

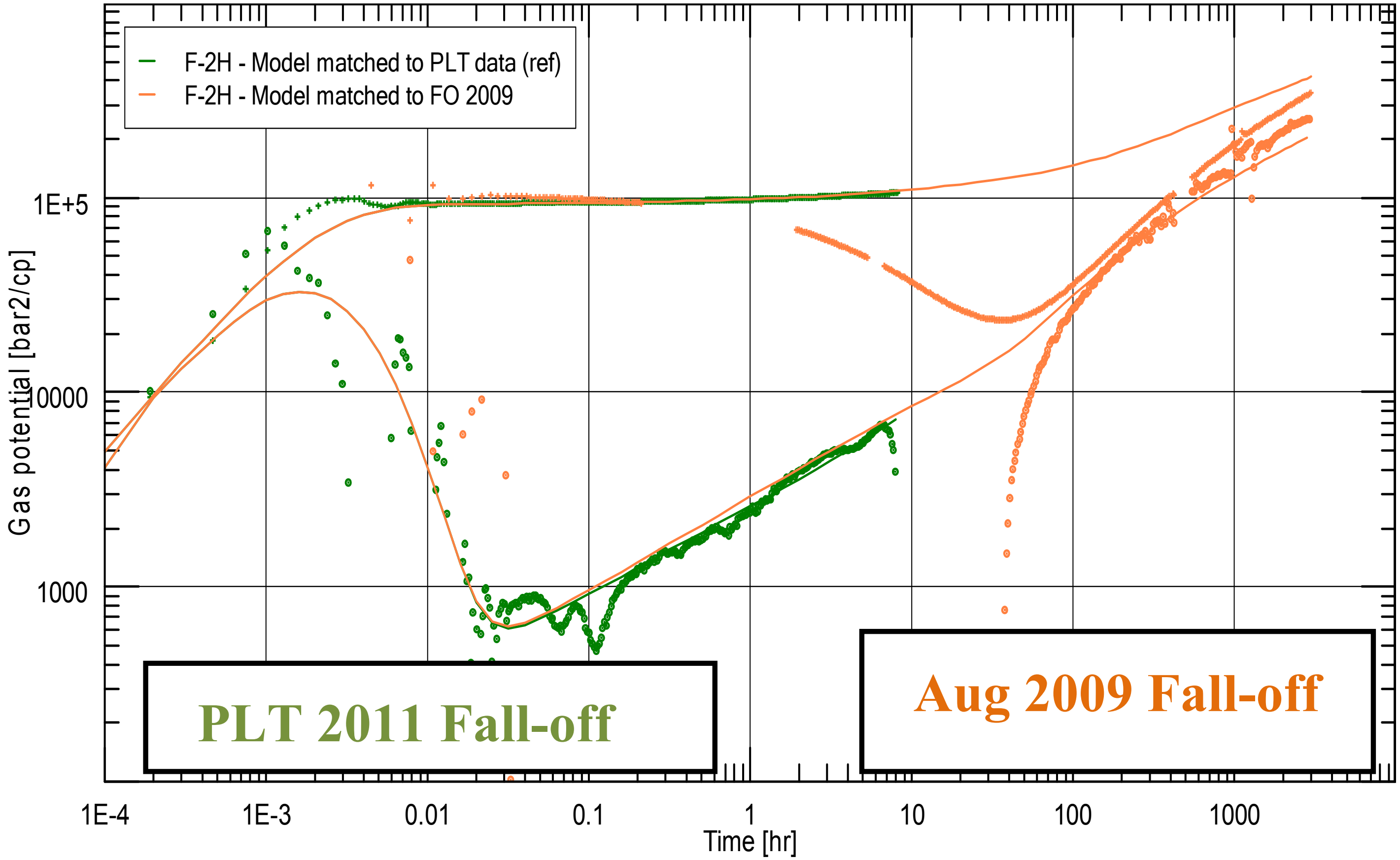
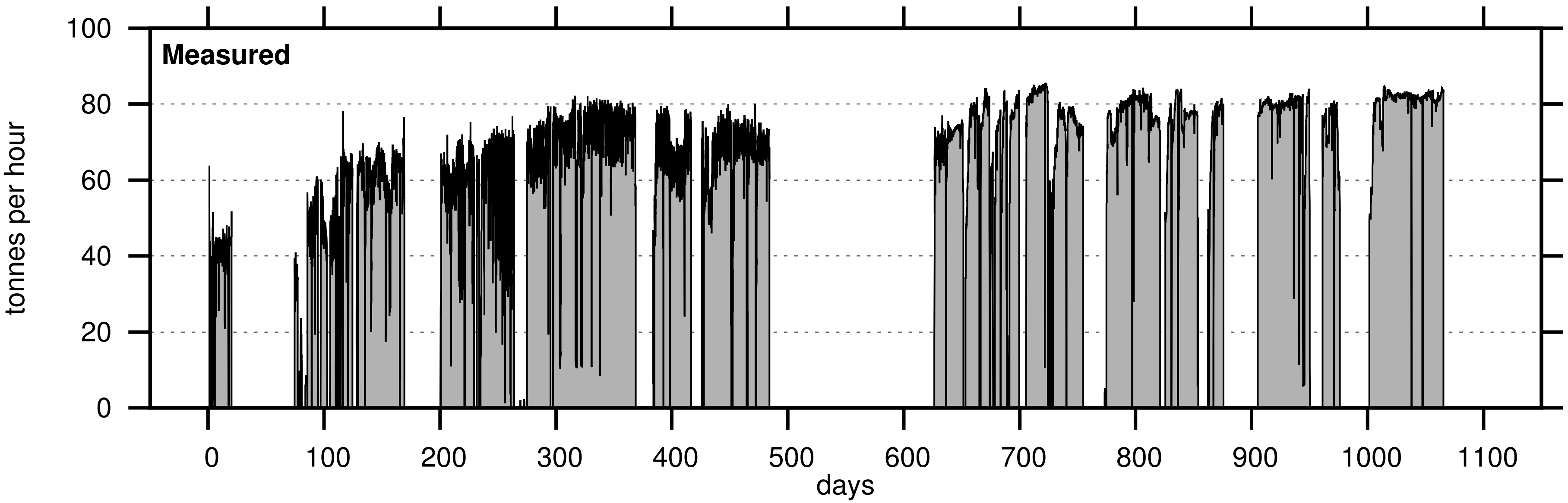


Figure: Falloff analyses using permanent gauge (2009) and PLT data (2011).

(Hansen et al. 2012)

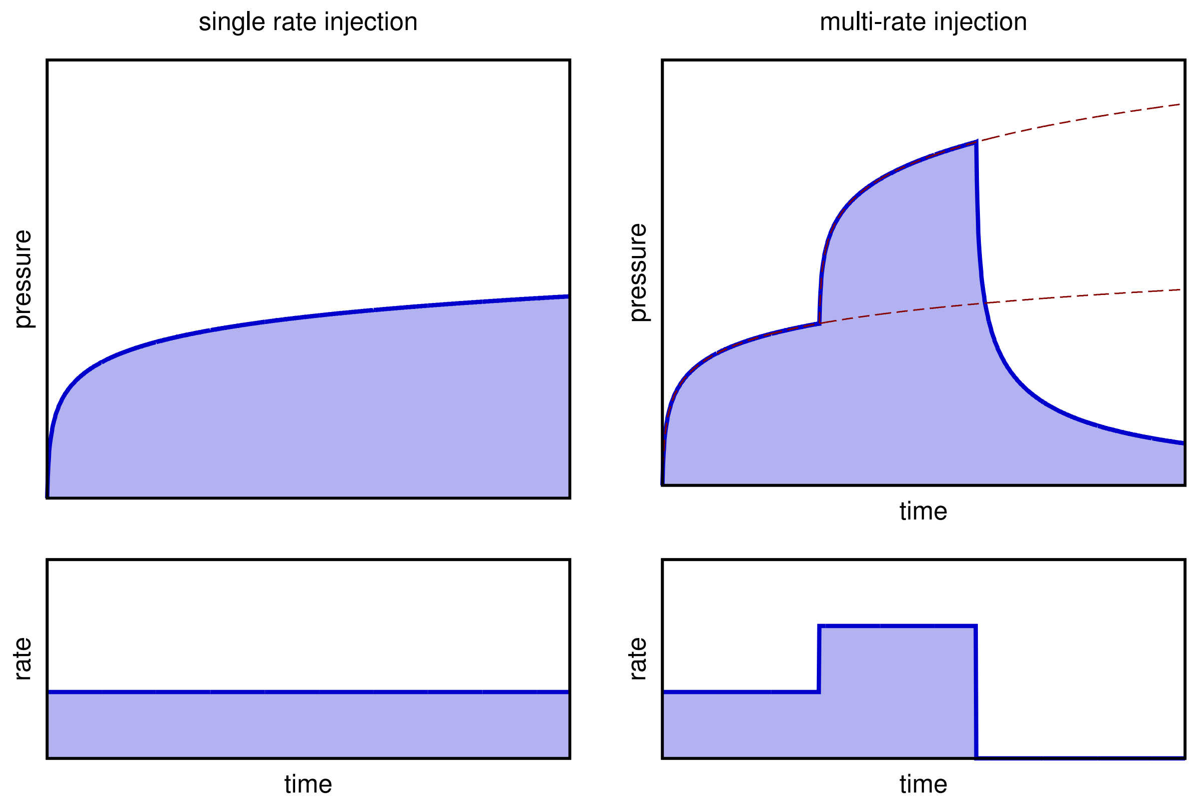
Falloff testing has proven value, but requires shutting in the well for significant periods



- **Motivating question:** Can we derive similar information from ongoing injection data, without shutting in for long periods?

Generalized superposition well-test method

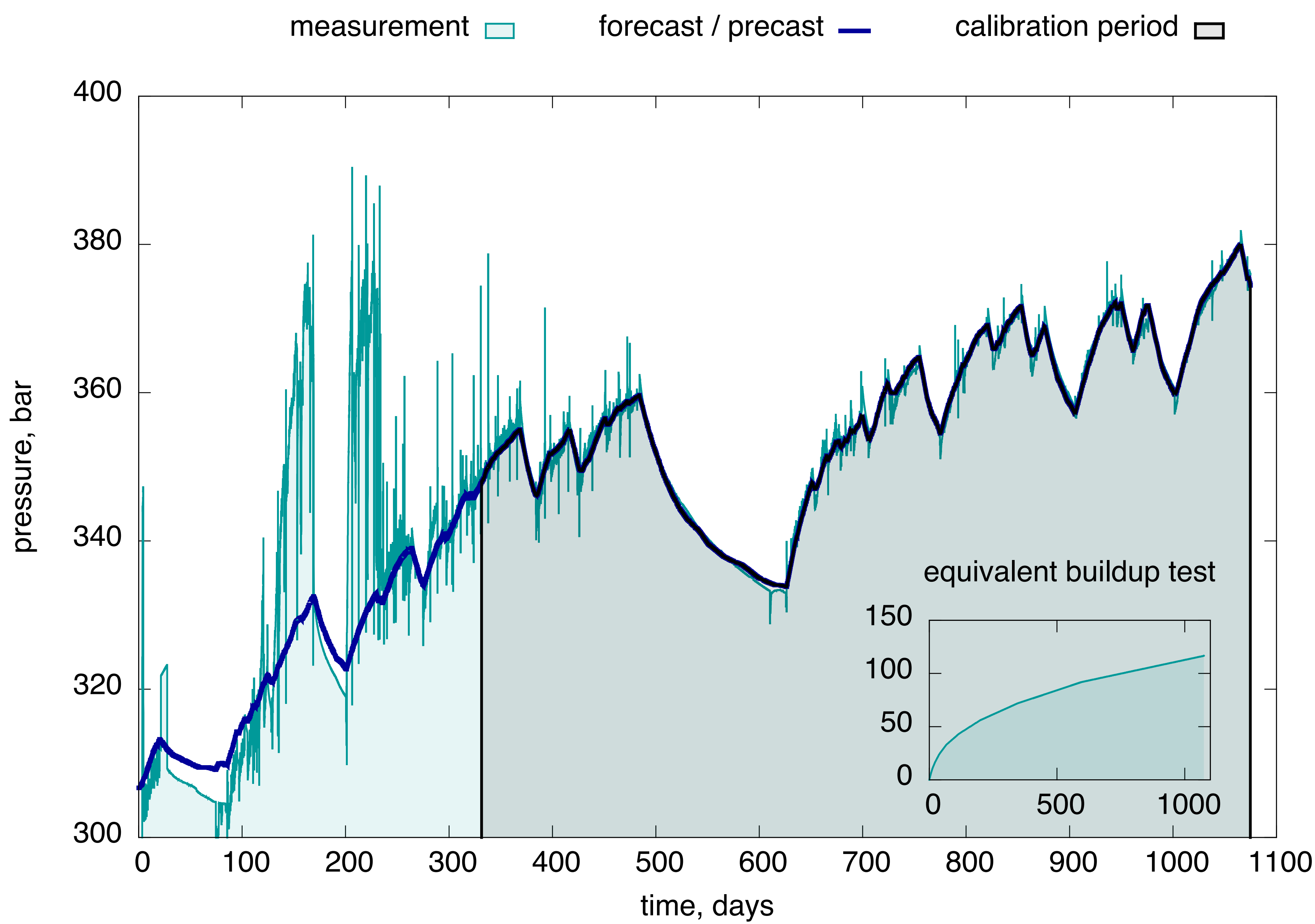
- Multi-rate injections are difficult to analyze.
- Can use superposition principle to transform a multi-rate injection into an “equivalent” single-rate test.
- Solve for a characteristic buildup curve, as a constrained least-squares problem.



Single rate: $$p(t) = q \cdot p_C(t)$$

Multi-rate: $$p(t) = \sum_i (q_{i+1} - q_i) \cdot p_C(t - t_i)$$

Automatic calibration to Snøhvit data (~5 seconds)



Superposition tool can potentially be used in two modes:

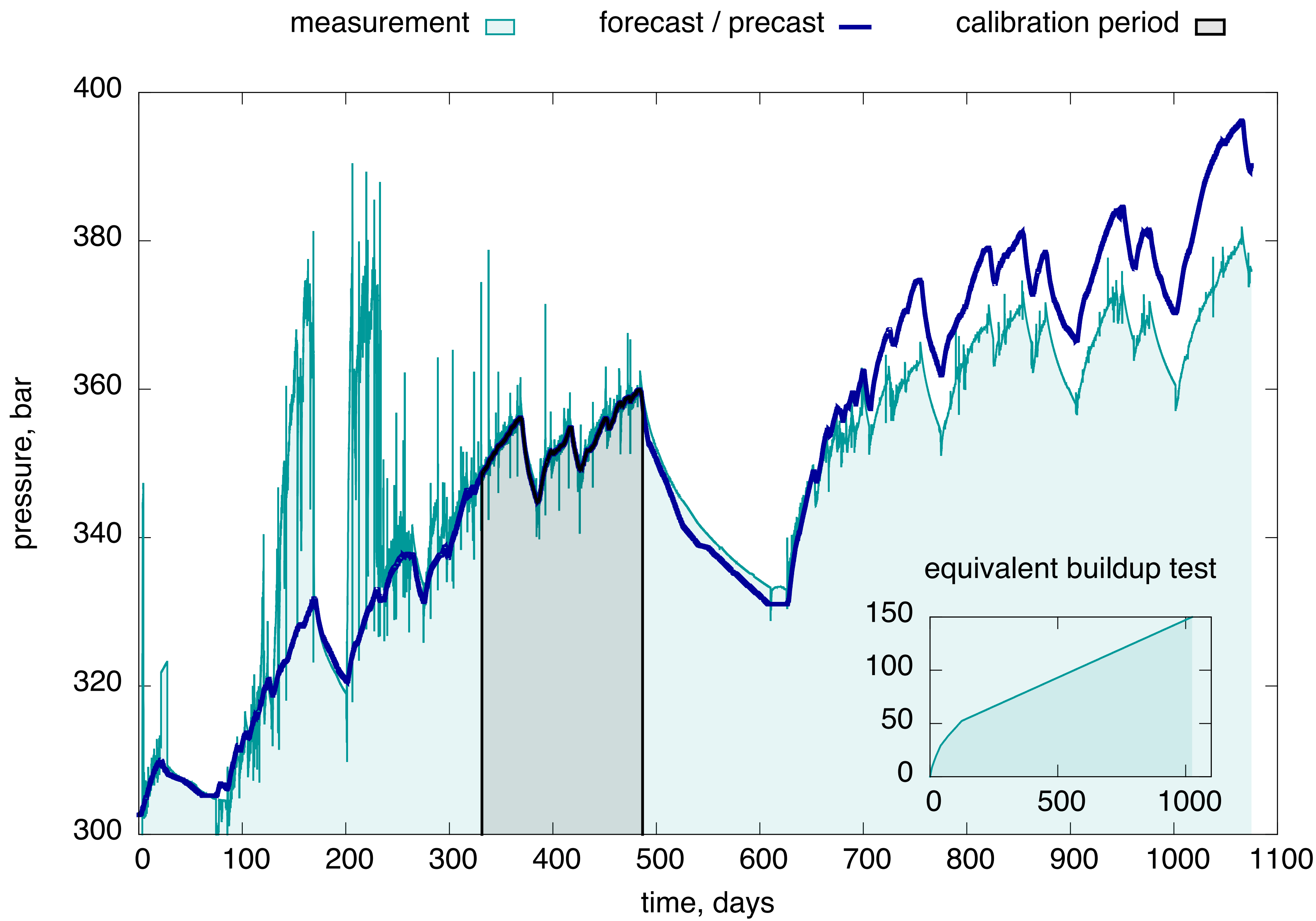
① **Reservoir characterization mode**

- Calibrate to gauge data, extract equivalent falloff test
- Apply standard well-test analysis techniques to results

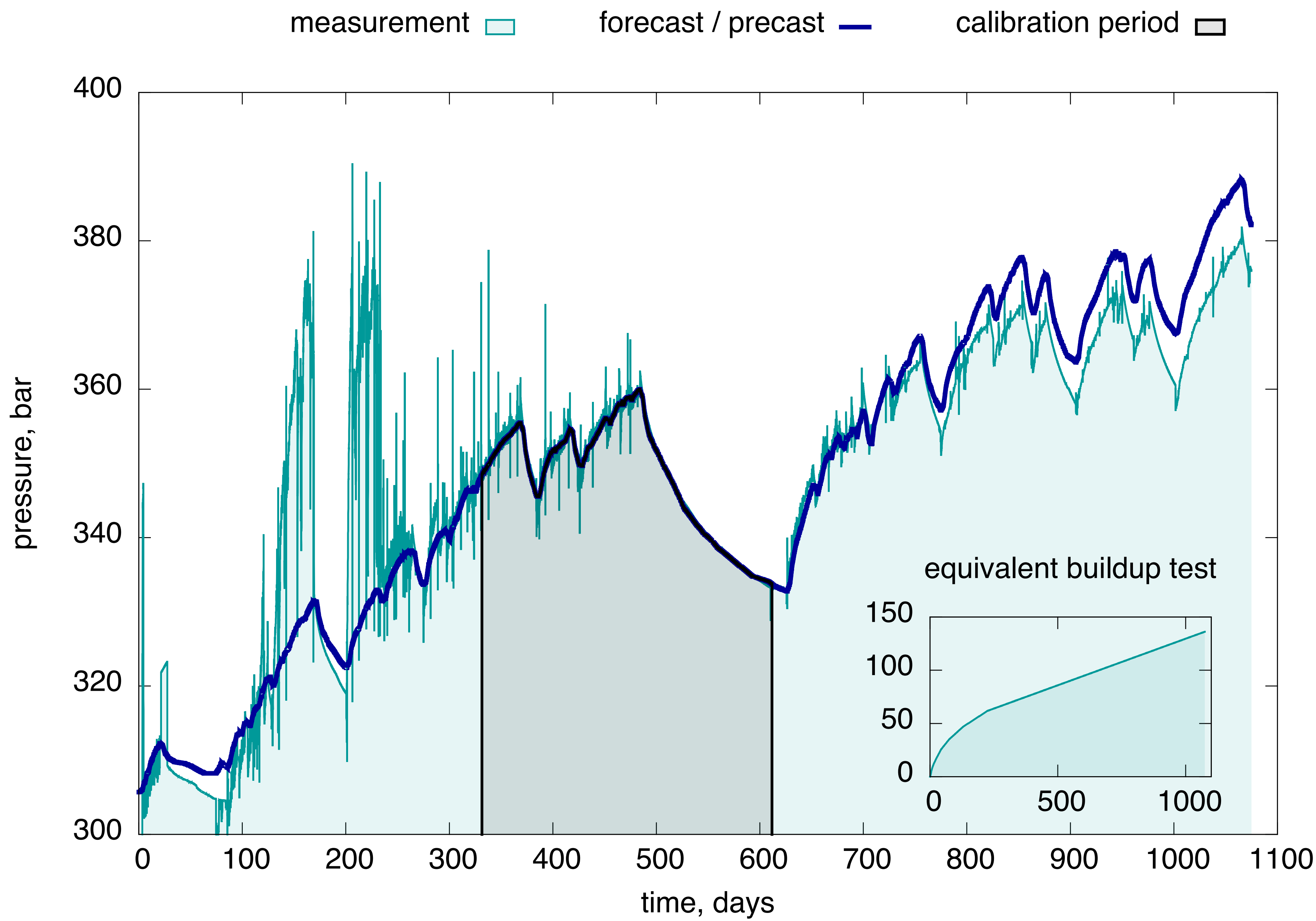
② **Pressure forecasting mode**

- Calibrate to gauge data, project forward in time
- Quickly explore alternative injection scenarios

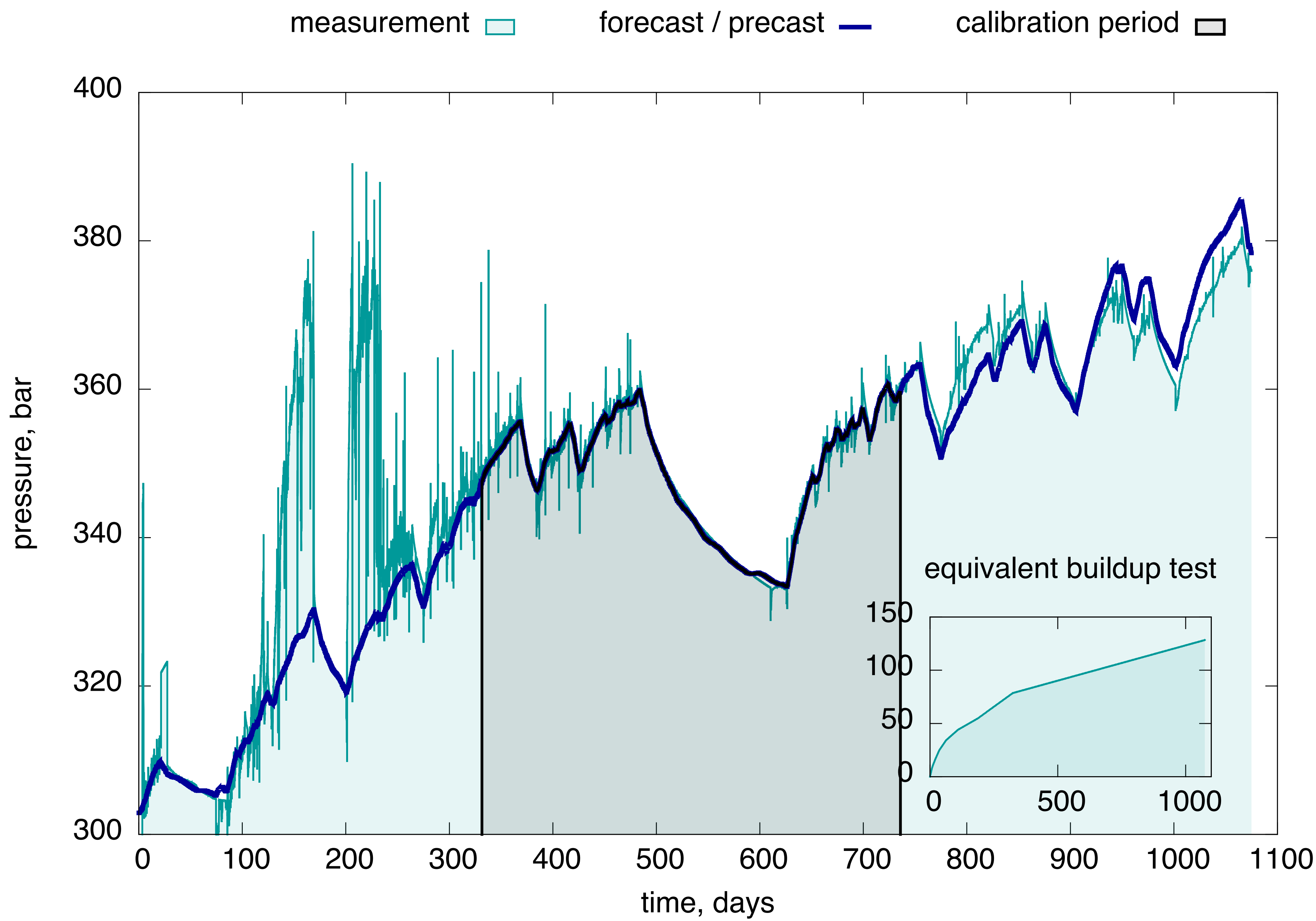
Fast-running pressure forecasting



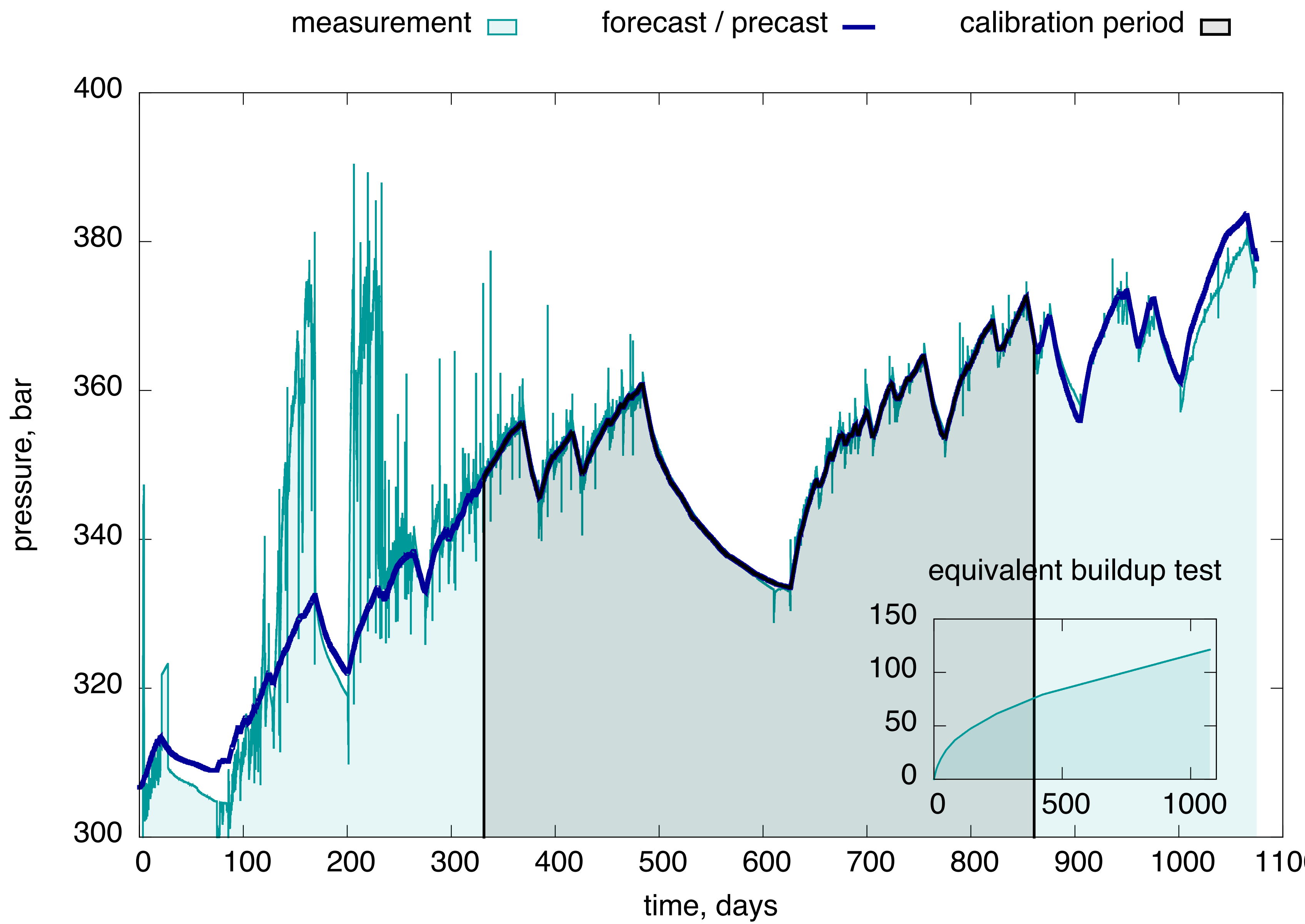
Fast-running pressure forecasting



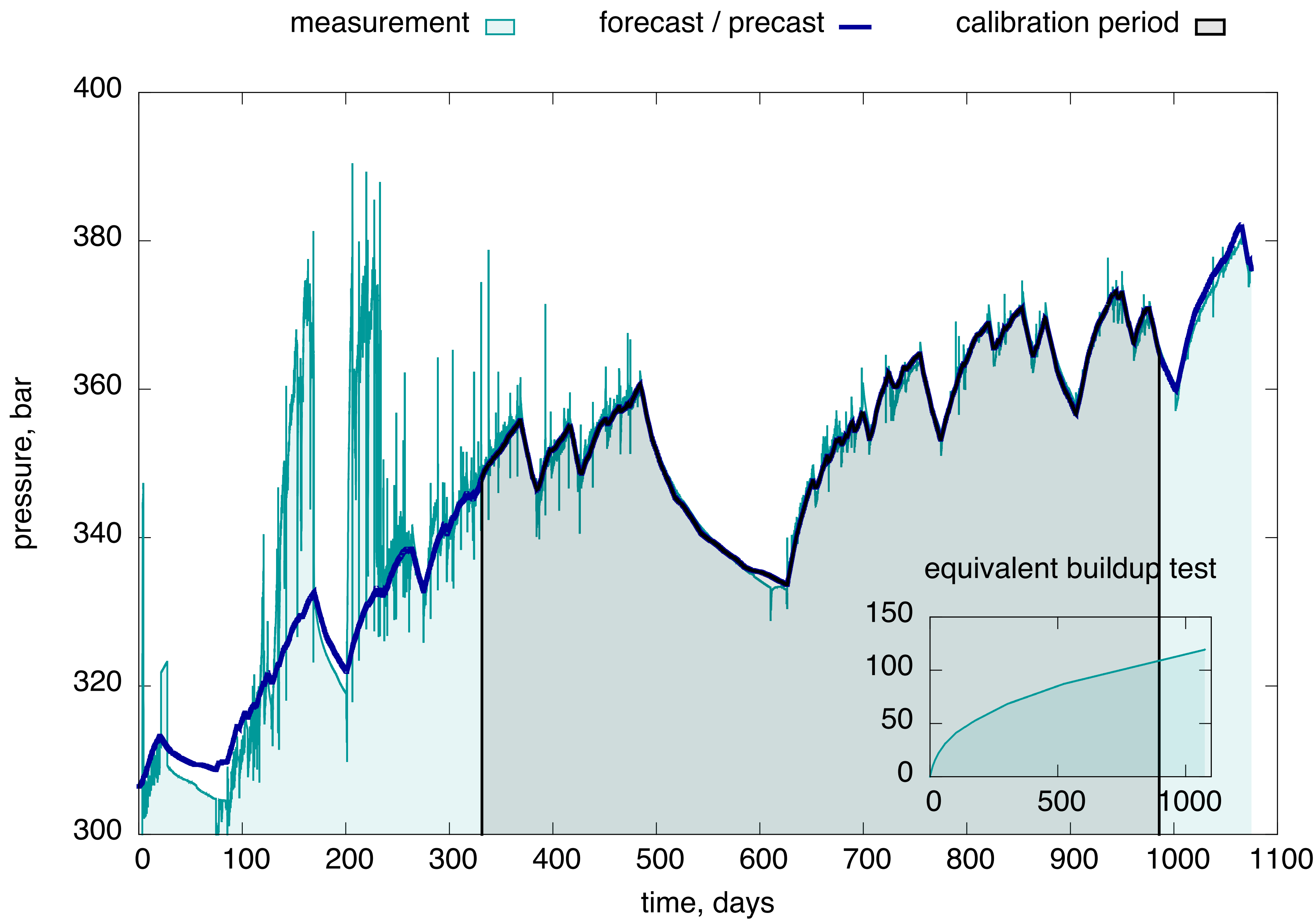
Fast-running pressure forecasting



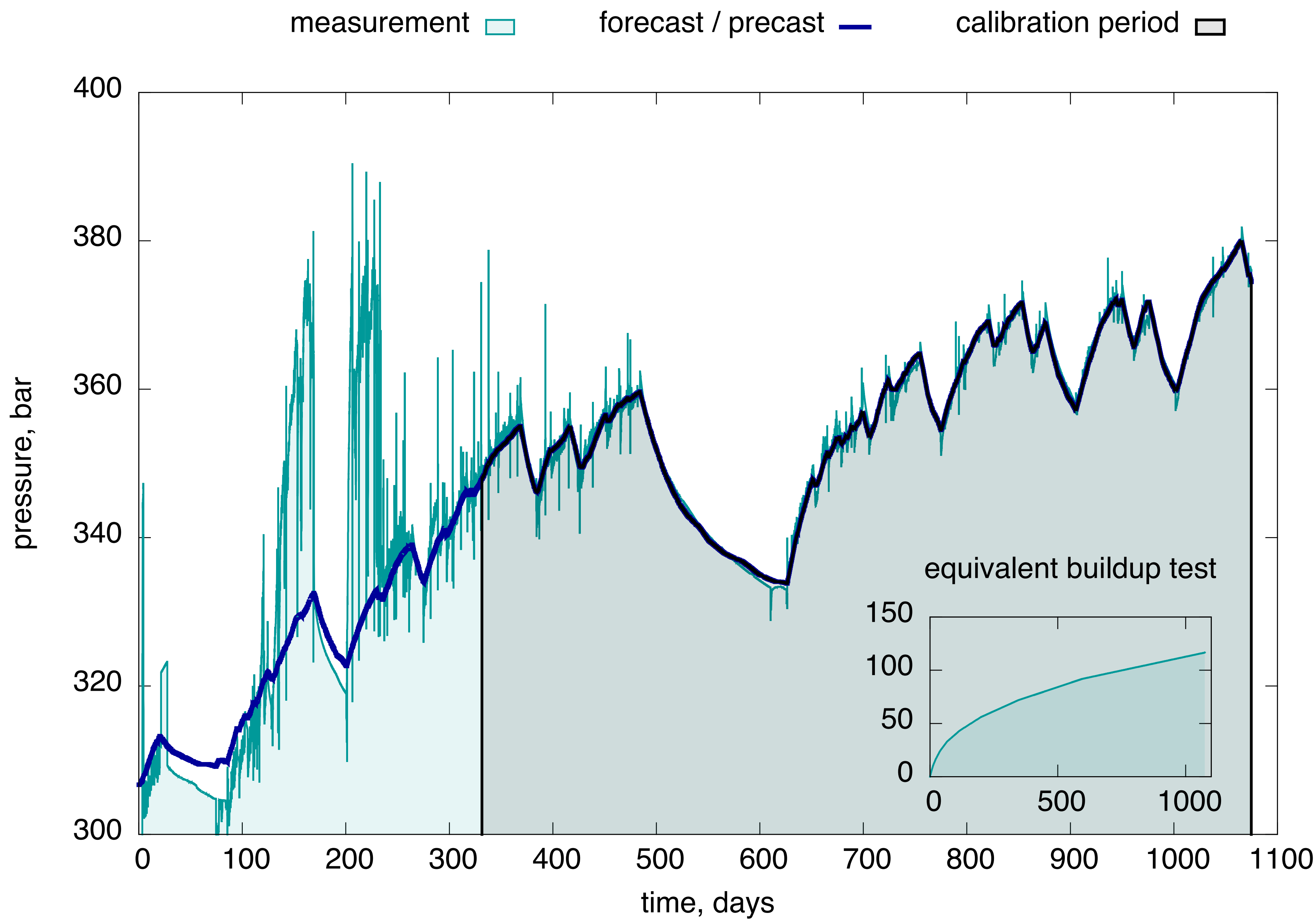
Fast-running pressure forecasting



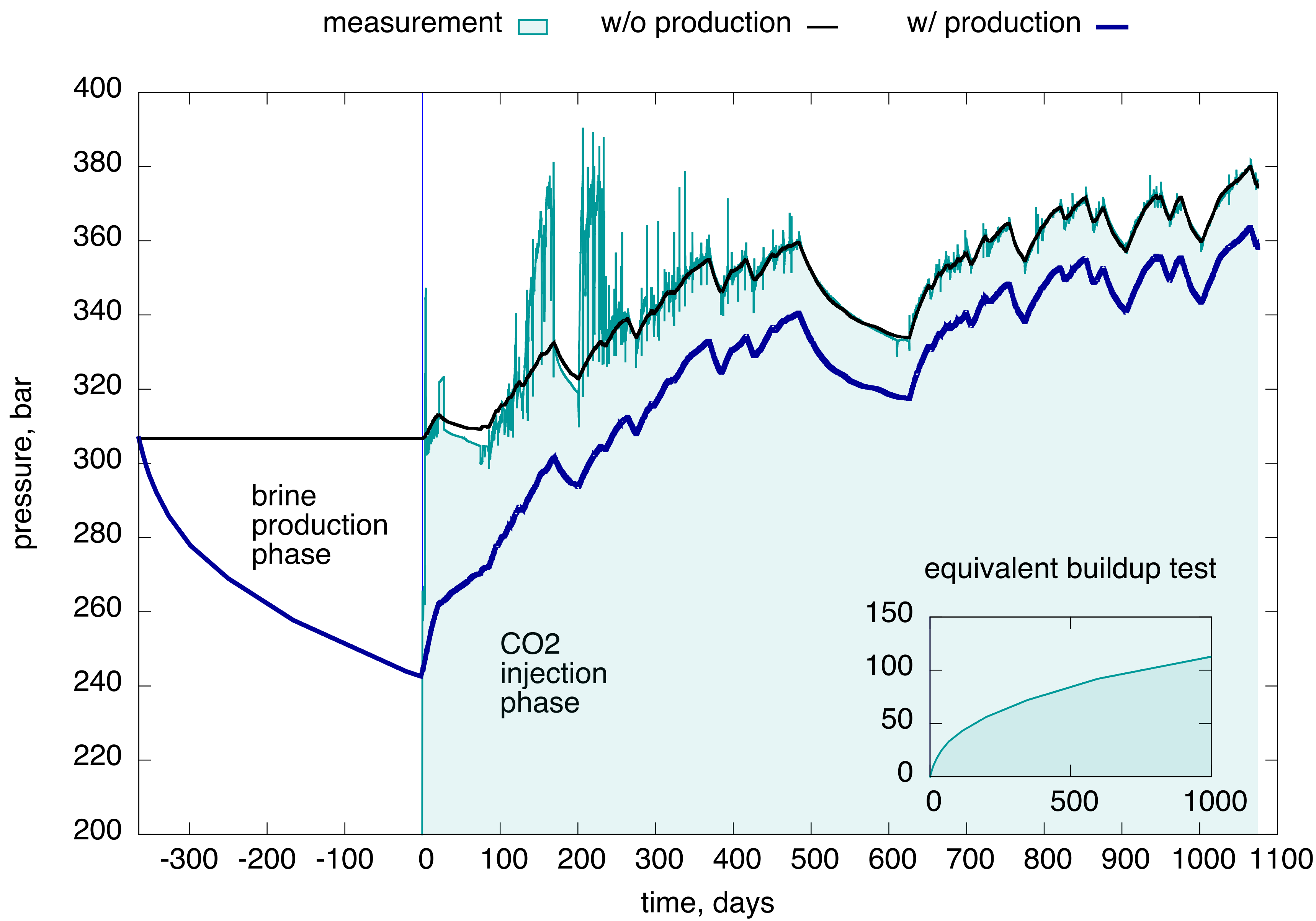
Fast-running pressure forecasting



Fast-running pressure forecasting



Retrospective analysis of a brine pre-production scenario



Summary

① **This project has explored two useful analysis techniques:**

- Probabilistic assessment of fault reactivation potential and in situ stress sensitivity

- dynamic well-test analyses using multi-rate gauge data

② **Directions for future work:**

- Full poromechanical simulations of fault reactivation and leakage.

- Relaxing current assumptions in the welltest analysis methodology to provide a more general tool.

Acknowledgements

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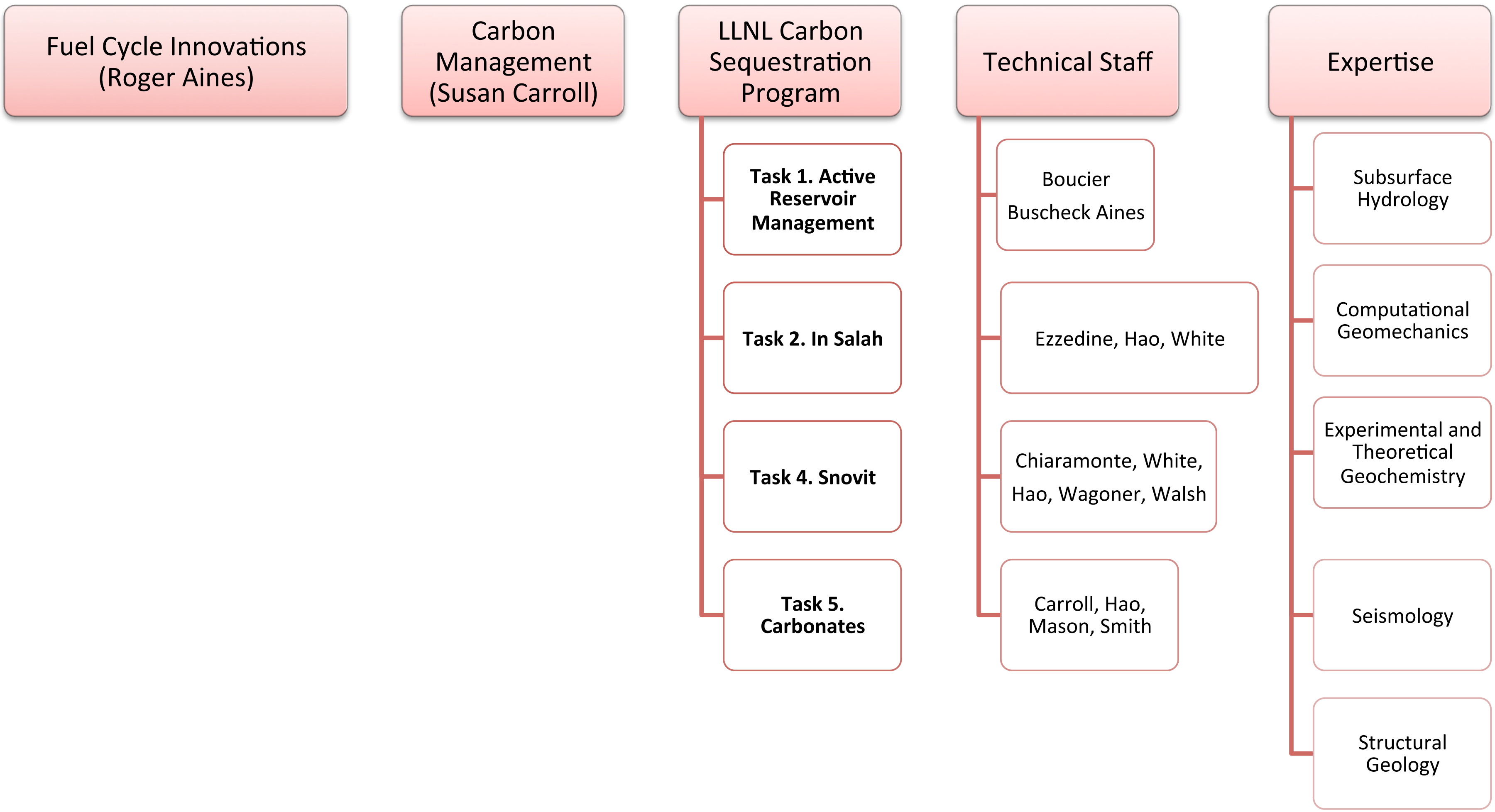
Appendix

Org Chart


Fuel Cycle Innovations (Roger Aines)
Carbon Management (Susan Carroll)
LLNL Carbon Sequestration Program
Task 1. Active Reservoir Management
Task 2. In Salah
Task 4. Snovit
Task 5. Carbonates
Technical Staff
Boucier
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Hao, Wagoner, Walsh
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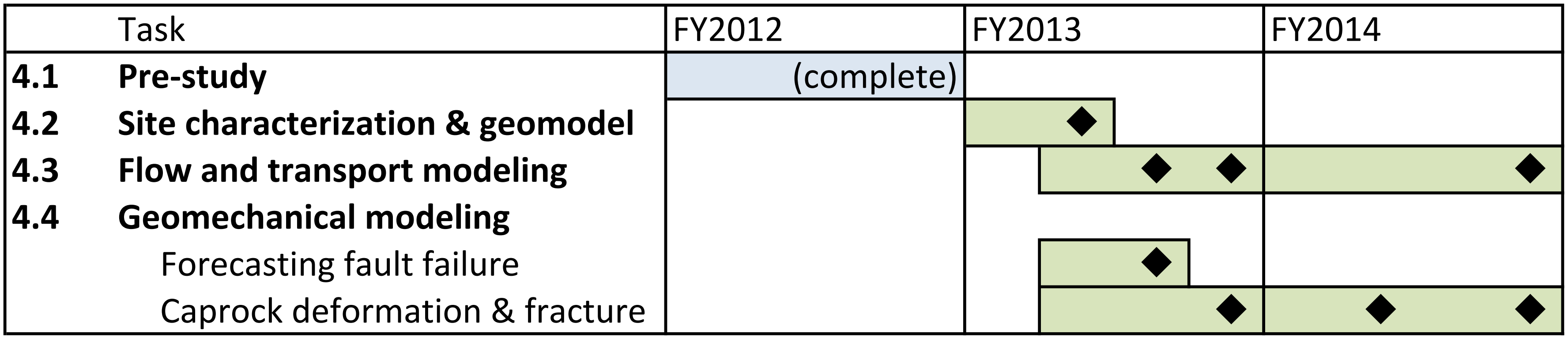
Expertise
Subsurface Hydrology
Computational Geomechanics
Experimental and Theoretical Geochemistry
Seismology
Structural Geology

Gantt Chart



- All technical tasks have been completed.
- In the final reporting stage:
  - Will submit final report and lessons-learned document by Sept 30, 2014.
  - Several journal manuscripts currently in review or preparation.

Bibliography

① Chiaramonte et al. (2014). Probabilistic geomechanical analysis of compartmentalization at the Snøhvit CO2 storage project. Submitted to JGR—Solid Earth.

② White et al. (2014). Generalized superposition welltest analysis. In preparation.

③ Numerous conference papers and abstracts.