NETL-RUA
Regional University Alliance

ConocoPhillips test results and data analysis

Brian J. Anderson

Associate Professor, Chemical Engineering, West Virginia University

NETL Carnegie Mellon PENNSTATE University of Pittsburgh VirginiaTech WestVirginiaUniversity URS

Overall Iġnik Sikumi Project Goals

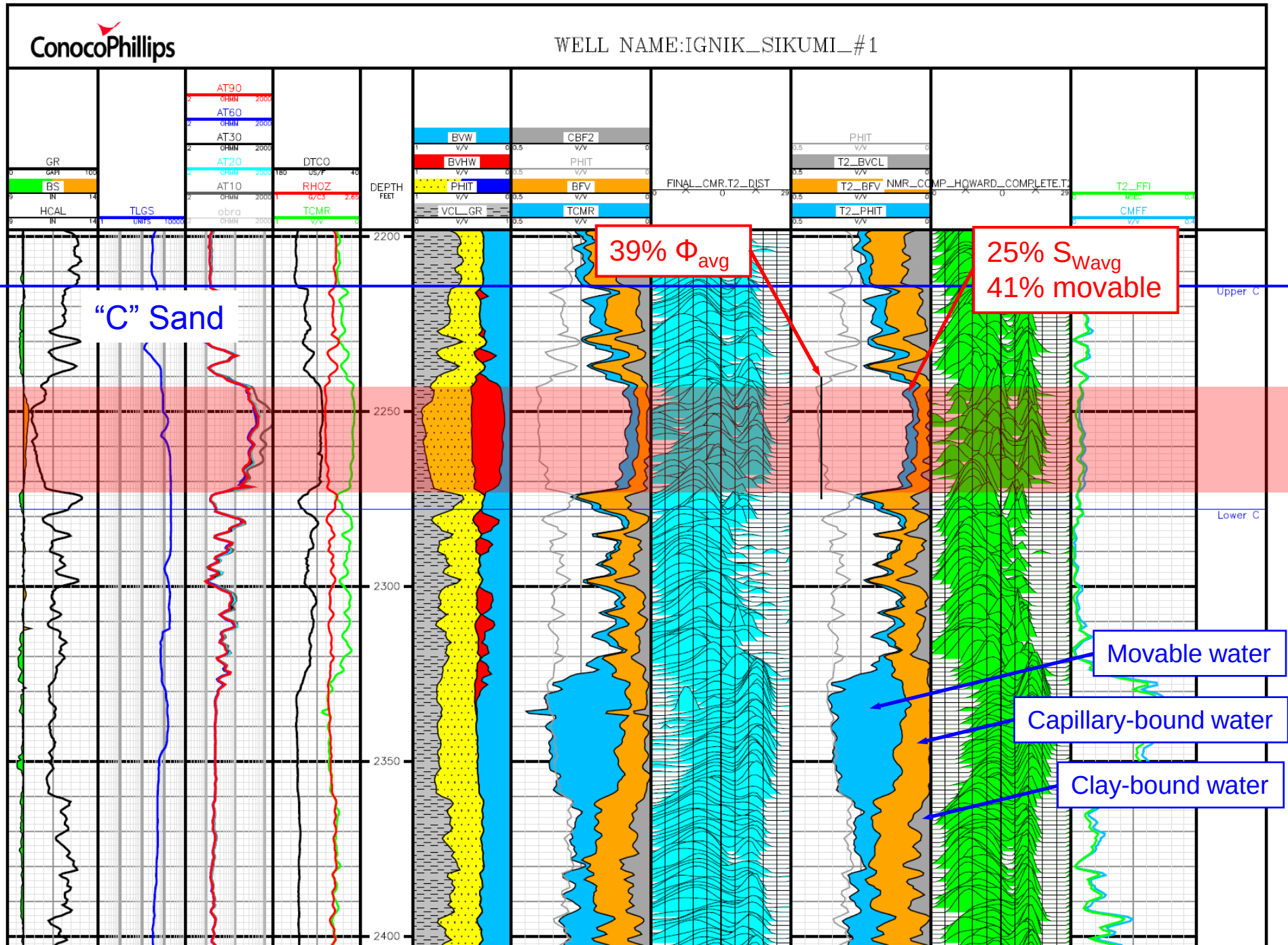
- **North Slope reservoir-scale field trial to evaluate CO_2/CH_4 exchange**
- **Short-term test to demonstrate concepts at larger-than-lab scale**
- **Validate exchange mechanism results from laboratory work**
  - Confirm injectivity into naturally occurring methane hydrates
  - Confirm methane release without production of water or sand
  - Obtain reaction rate data to facilitate reservoir-scale modeling
- **Demonstrate stable production of natural gas hydrates by depressurization**

Project History

- **2008 – 2010**
  - Select site and gain access
  - Characterize reservoir
- **2011**
  - Drill, log, complete and suspend Iġnik Sikumi #1
  - Design field test
- **2012**
  - Re-enter well and perforate
  - Perform exchange test
  - Perform depressurization test
  - P & A well and remediate site
  - Prepare datasets
  - Begin data analysis
- **2013**
  - Data analysis and history matching

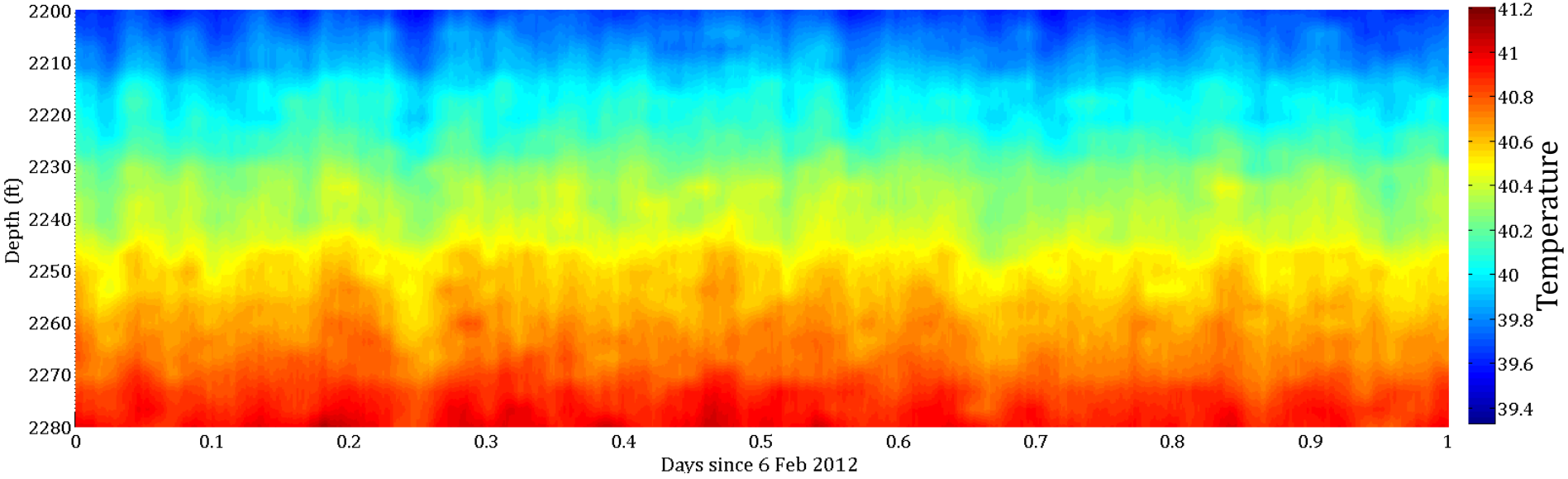
July 2012 Status

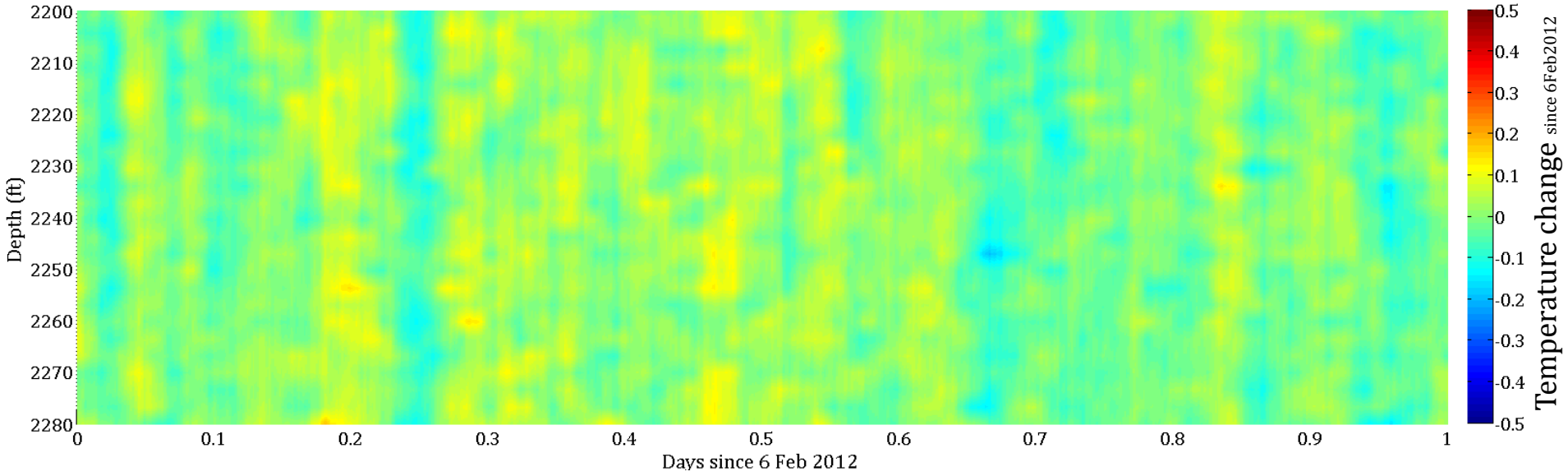
- **Data Correction/Reconsolidation in Progress**
  - Outliers/spikes removed
  - Time stamps for each source corrected
  - GC data reprocessed
  - Three DTS data sets obtained
    - Un-normalized and 2 types of normalization
  - Created 1 and 5 min time average datasets
  - Adding corrections for dead volumes/wellbore storage
- **Path Forward**
  - Perform material balance of test
  - Injectivity analysis, using simulation
    - Infer hydrate saturation changes
  - Production analysis using cell-to-cell model
    - Gas phase composition history match
  - Issue final database and report
  - DOE workshop


ConocoPhillips
WELL NAME:IGNIK_SIKUMI_#1
GR
BS
HCAL
TLGS
AT90
AT60
AT30
AT20
AT10
obra
DTCO
RHOZ
TCMR
DEPTH
FEET
BVW
BVHW
PHIT
VCL_GR
CBF2
PHIT
BFV
TCMR
FINAL_CMR.T2_DIST
PHIT
T2_BVCL
T2_BFV
T2_PHIT
NMR_COMP_HOWARD_COMPLETE.T2
T2_FFI
CMFF
2200
2250
2300
2350
2400
Upper C
Lower C
"C" Sand
39% Φavg
25% SWavg
41% movable
Movable water
Capillary-bound water
Clay-bound water

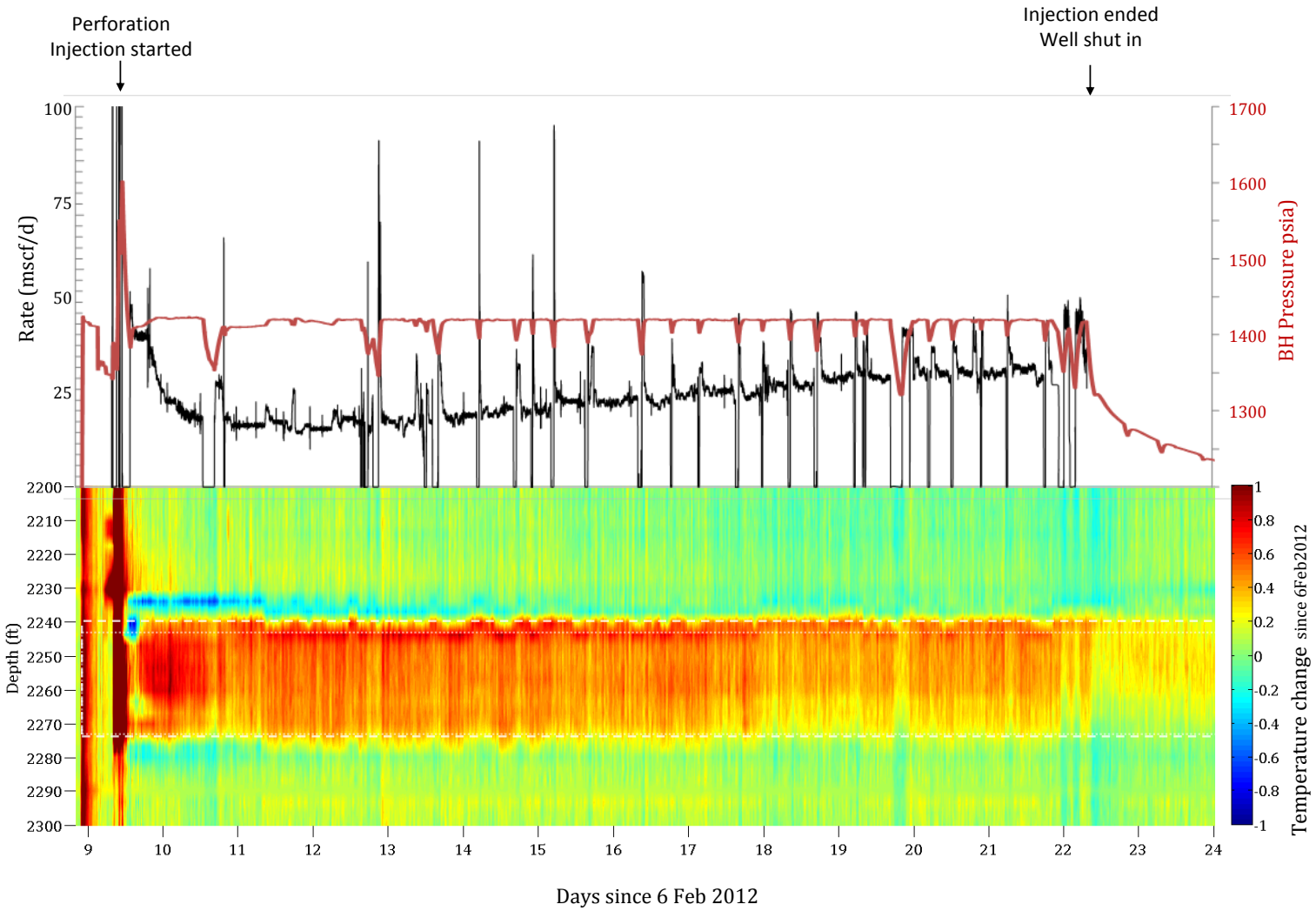
Initial Period before any well work

Temperature linear with geothermal gradient (~1.79°F/100ft), Temperature change ~0

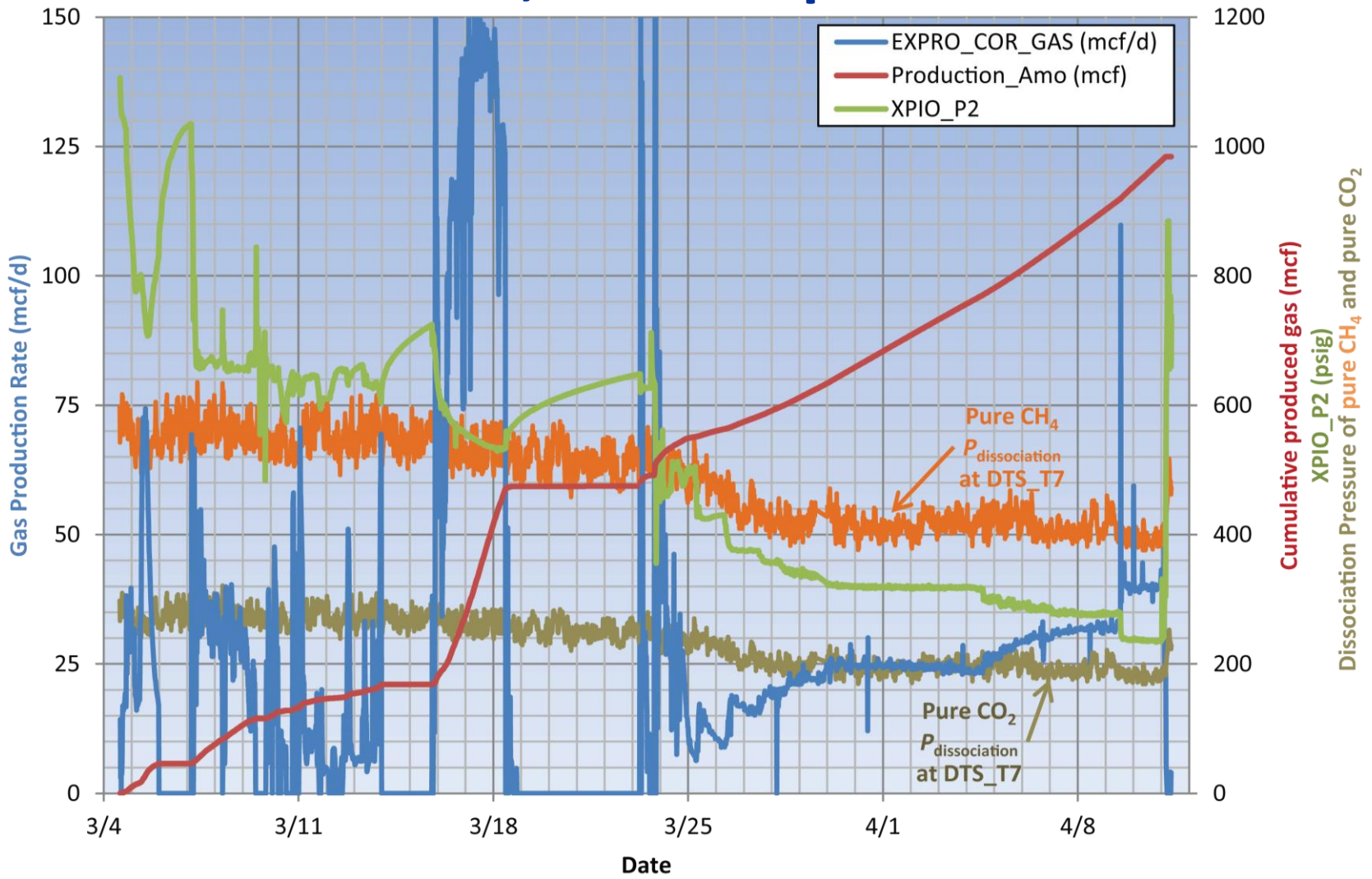




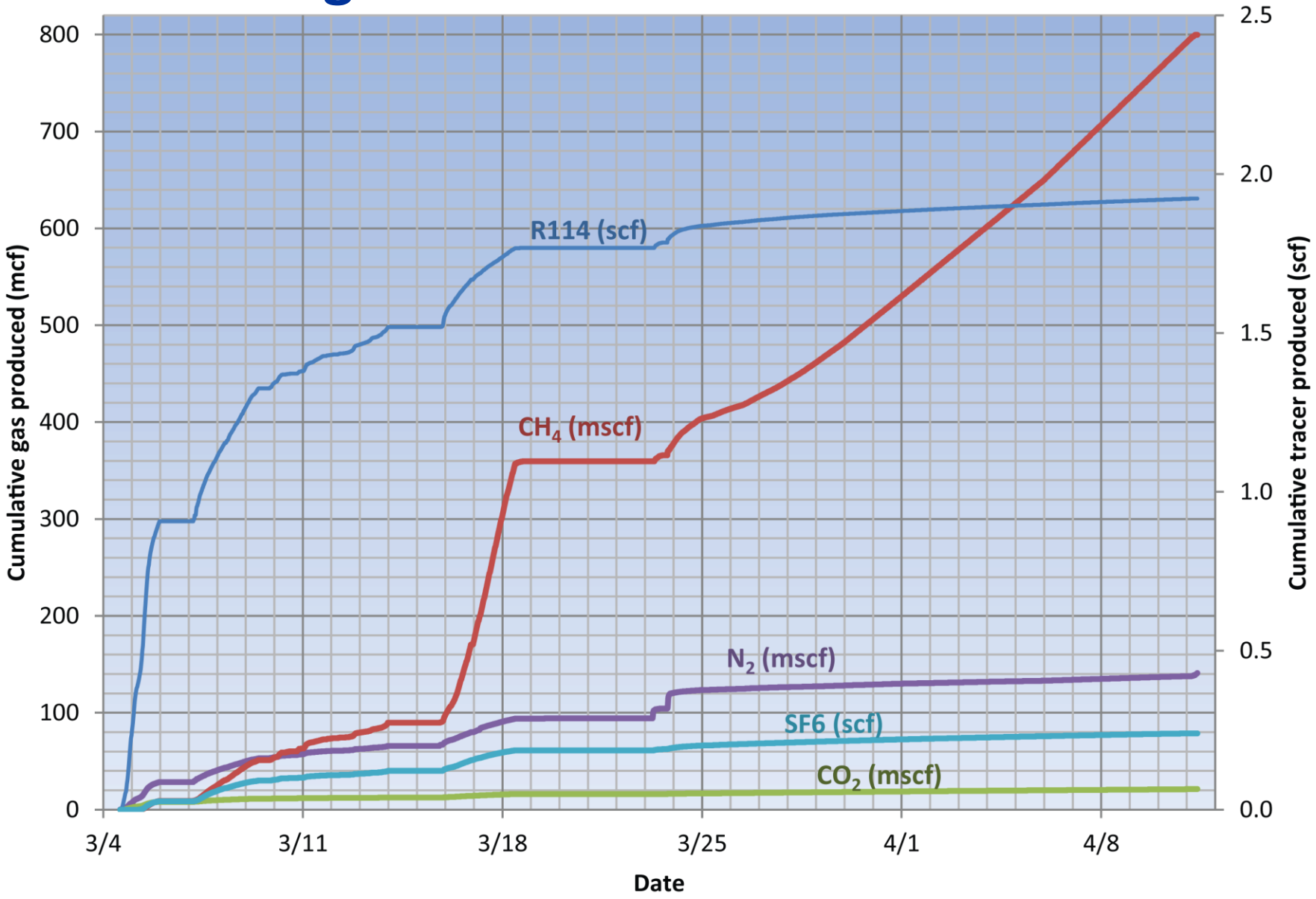
Injection


Perforation
Injection started
Injection ended
Well shut in
Rate (mscf/d)
BH Pressure psia)
Depth (ft)
Temperature change since 6Feb2012
Days since 6 Feb 2012

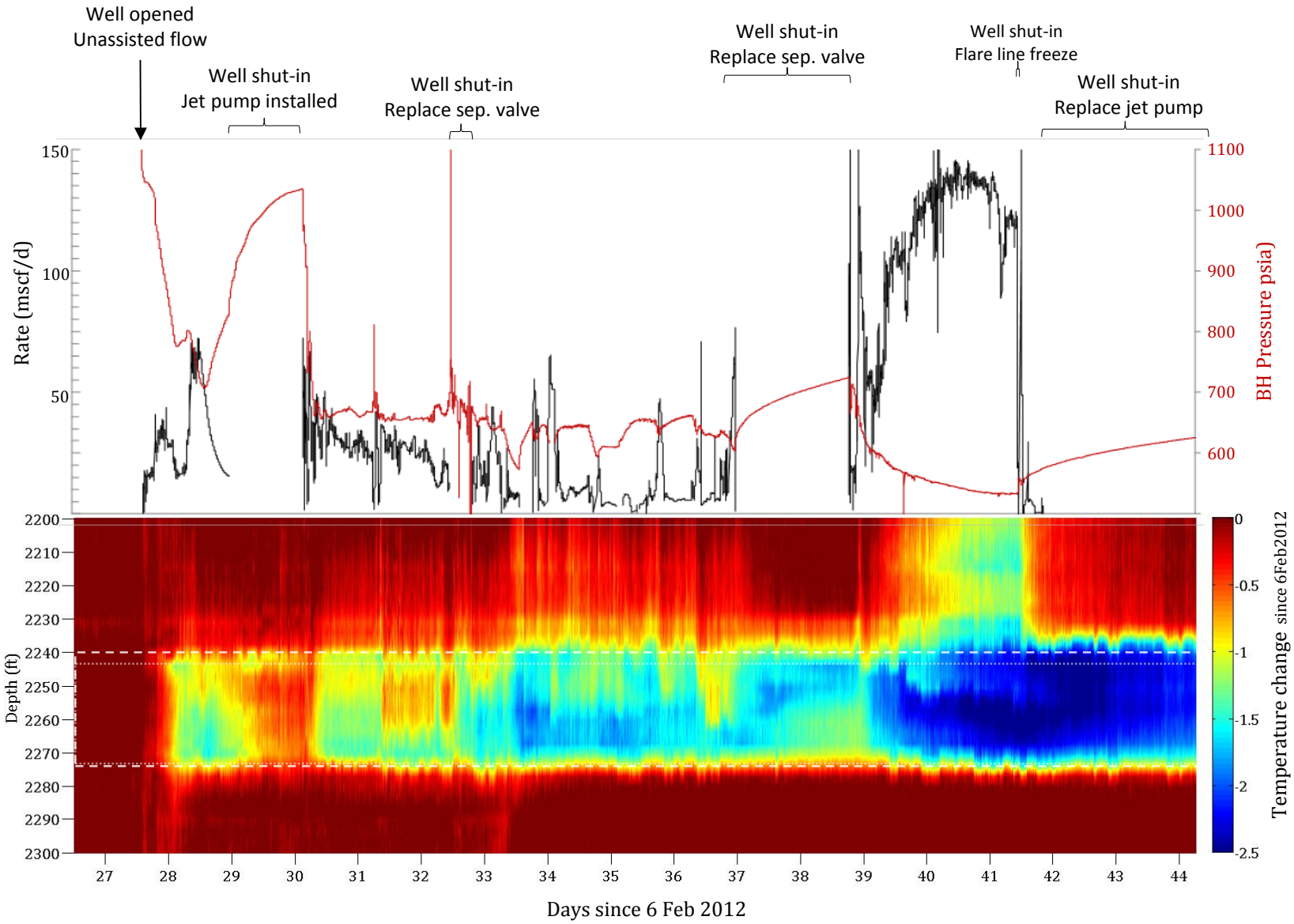
Overall Production – Gas rates, Pressure, and Temperature



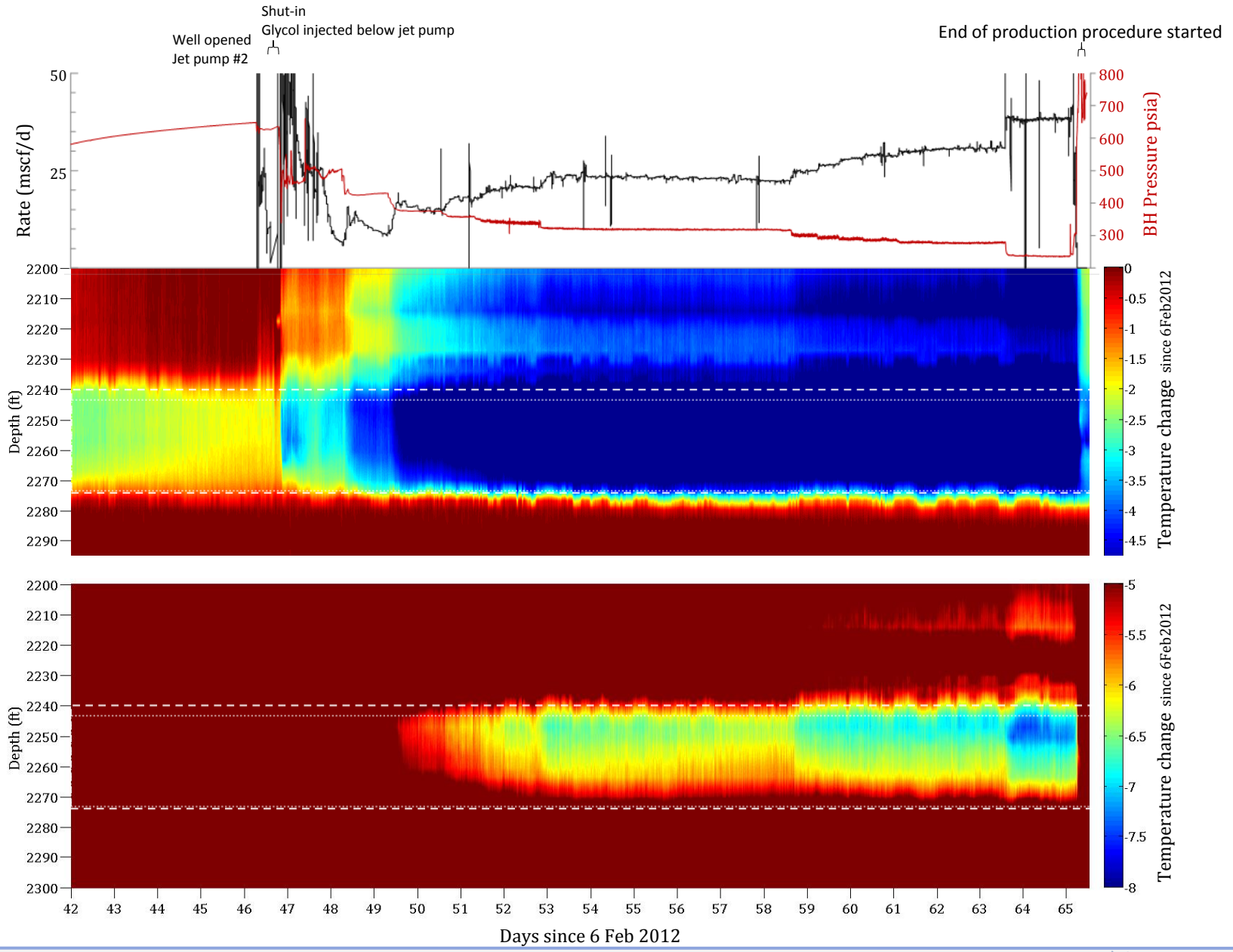
Ignik Sikumi #1 Production



Flowback - Production Period #1



Flowback - Production Period #2



Summary Observations

- Successful injection of CO_2 mixture into hydrate reservoir
- Methane produced both above / below CH_4-stability pressure
  - CO_2 was retained in the reservoir compared with N_2
    - Indicates the possibility of CO_2 exchange
- Depressurization sustained below CH_4-stability pressure
  - Steady increase in production rate
  - Over 850 mscf (24,000 scm) of CH_4 produced in total
  - Low BHP achieved (~250 psi)
- Solids production significant
- Evidence for heterogeneous injection / production

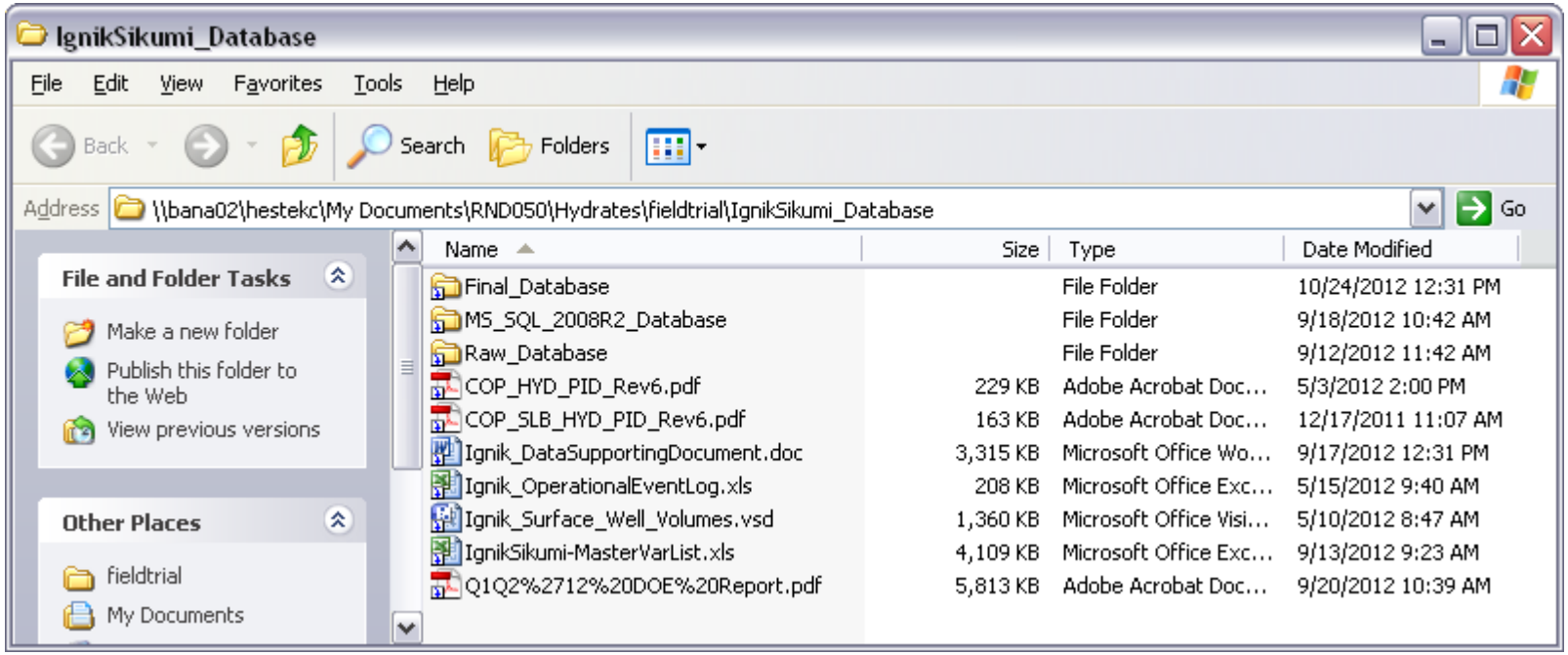
Database Summary

- **Diagrams of the operations included**
  - PI&D's + dead volumes of surface equipment and well
- **Master Variable List**
  - Where to go for complete info on any recorded variable
    - e.g., what instrument recorded the data, calibration, etc
- **Supporting Data Document**
  - Where to go for notes on calculations and data corrections
- **Operation Event Log**
  - Where to go to see what was happening at every step of the test
- **All raw data in MySQL and CSV format**
- **All final data available in MS SQL database format, CSV, Matlab**
  - Clean, 1 min averaged, and 5 min averaged data

Data Streams

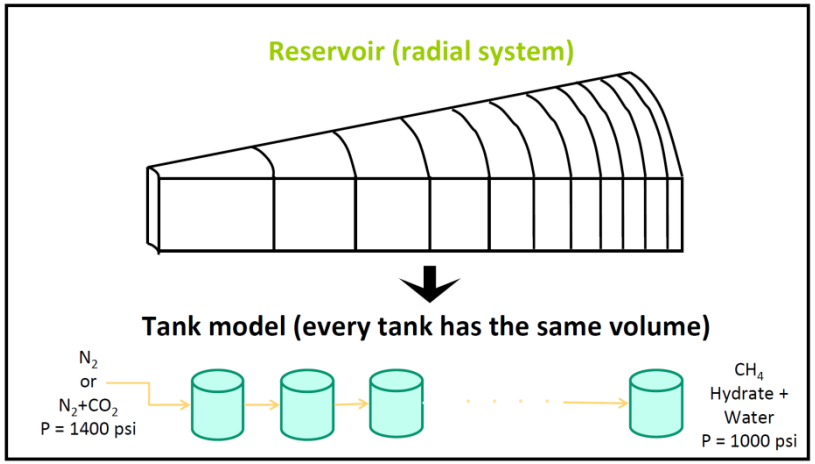
- **Composition**
  - On-line GC (~15 min sampling int.)
- **Continuous downhole conditions**
  - 3 downhole pressure gauges (P&T)
  - Distributed Temperature Sensing (T per ft)
- **Continuous surface conditions**
  - Pump rates
  - Flow rates (gas, jet pump fluid)
  - Line pressures and temperatures
  - Separator P&T
- **Produced fluid measurements**
  - Collected on regular intervals
  - Water prod rate
    - Tank straps (~30min int.)
  - Water (~1hr int.)
    - pH, salinity, SG
  - Gas (~1hr int.)
    - Gas gravity

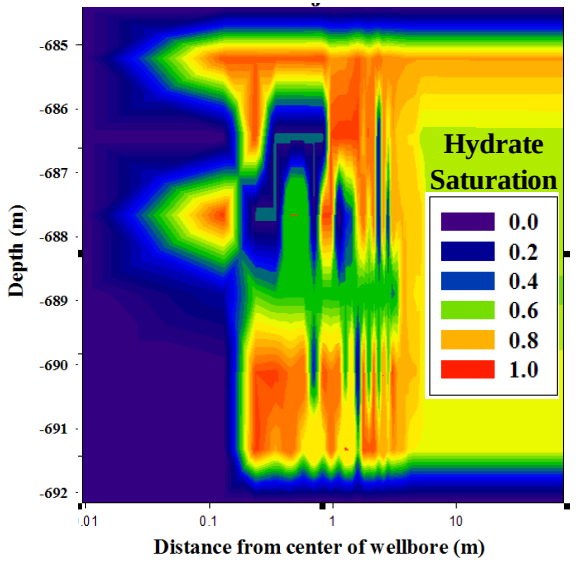
Database Folder



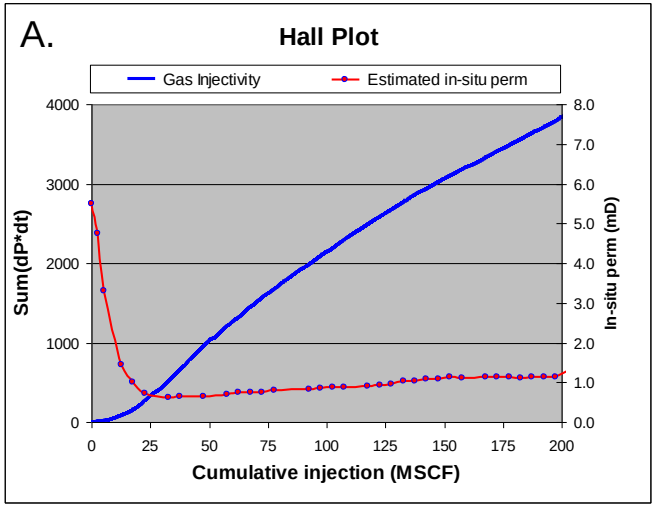
Modeling and Simulation Efforts

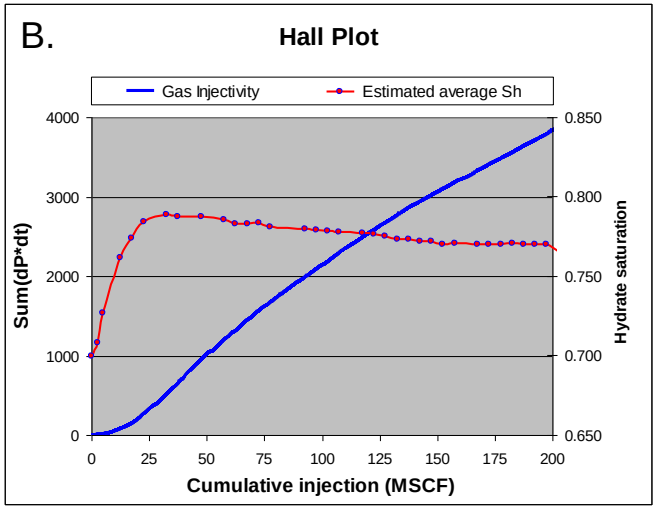
- Adiabatic CTC Model (ConocoPhillips)
  - Cell Volume (3.5 ft), S_H = 65%, P_i = 1000 psi, T_i = 40.5 F
- Solids production
- Heterogeneous production
- History-match simulations of the Iġnik Sikumi field test with newly-developed Mix3HRS software
- Complex pressure, temperature, and composition history
  - CO_2+N_2 injected into a CH_4 reservoir with all 3 gases produced
  - Competing thermodynamics for hydrate formation and dissociation in the reservoir



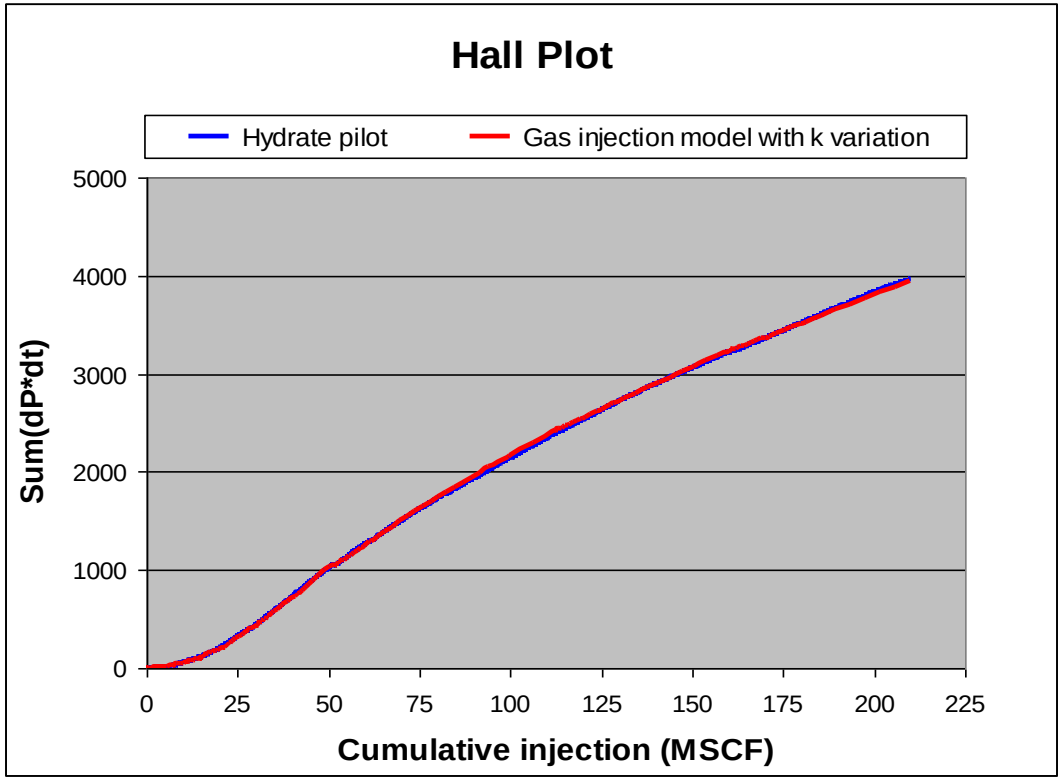


Hall Plot – Varying Permeability



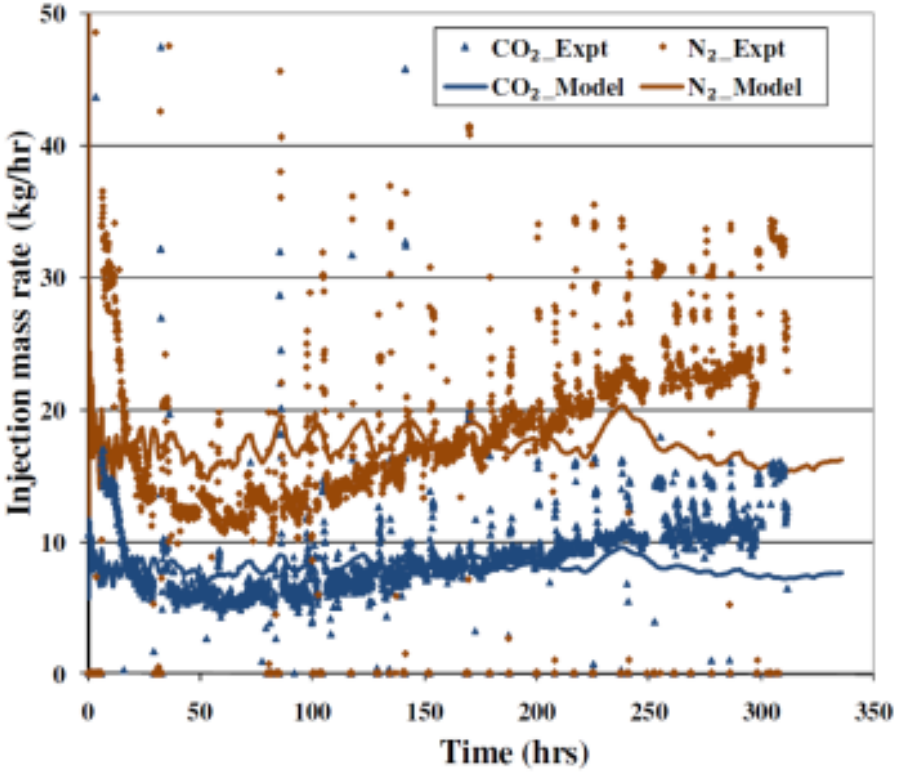


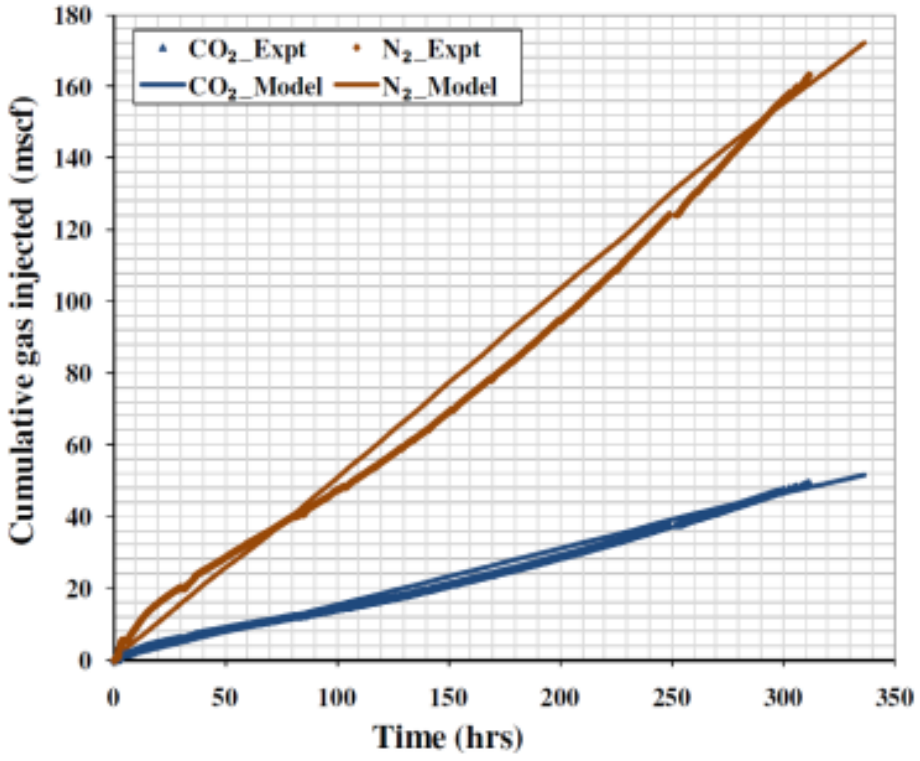
- Permeability adjusted over time
- One possibility is Δ hydrate sat.
- Good match obtained



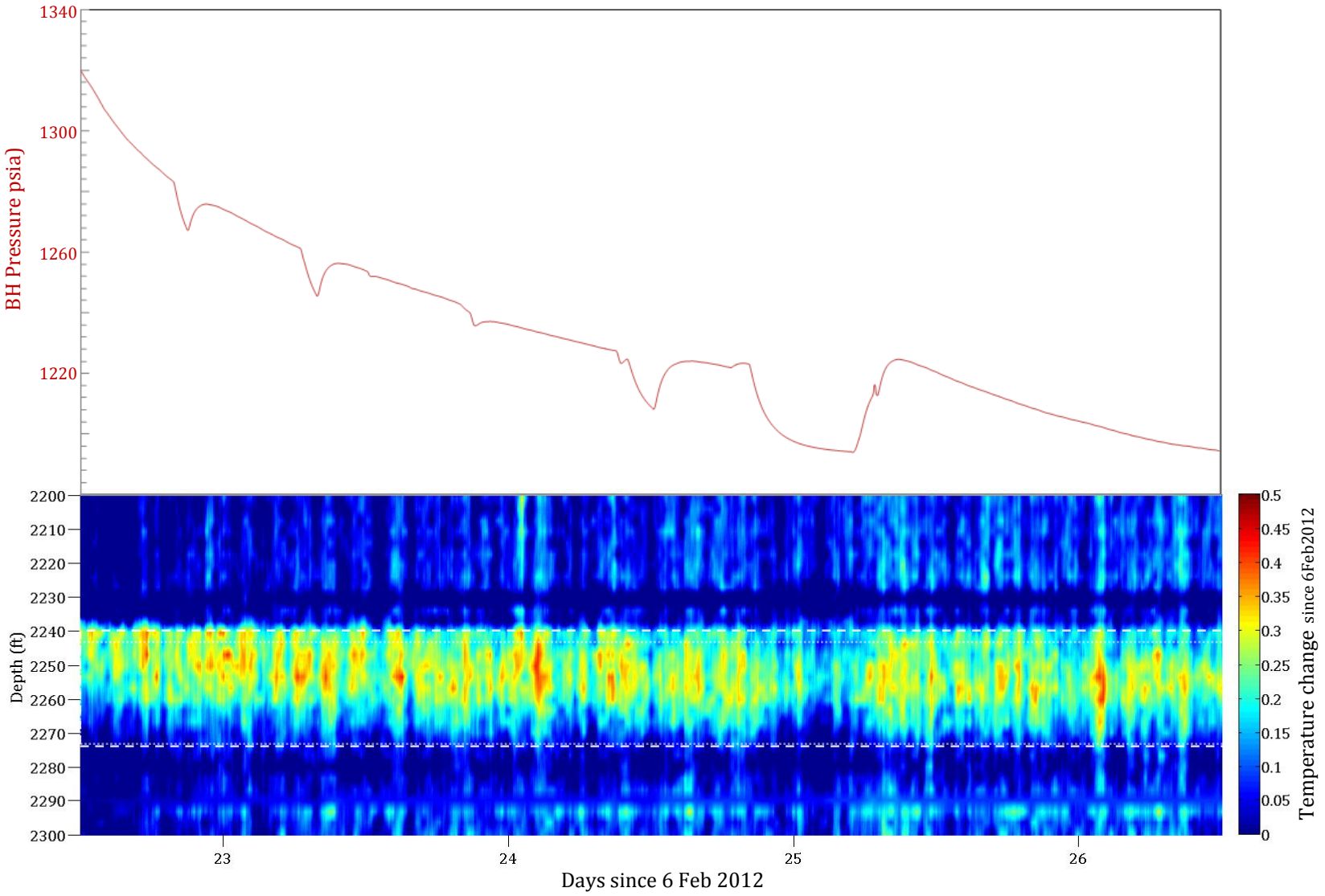
Injection matching

- The Injection flow rate and cumulative injection of CO_2 and N_2 into the reservoir are matched with the field data.

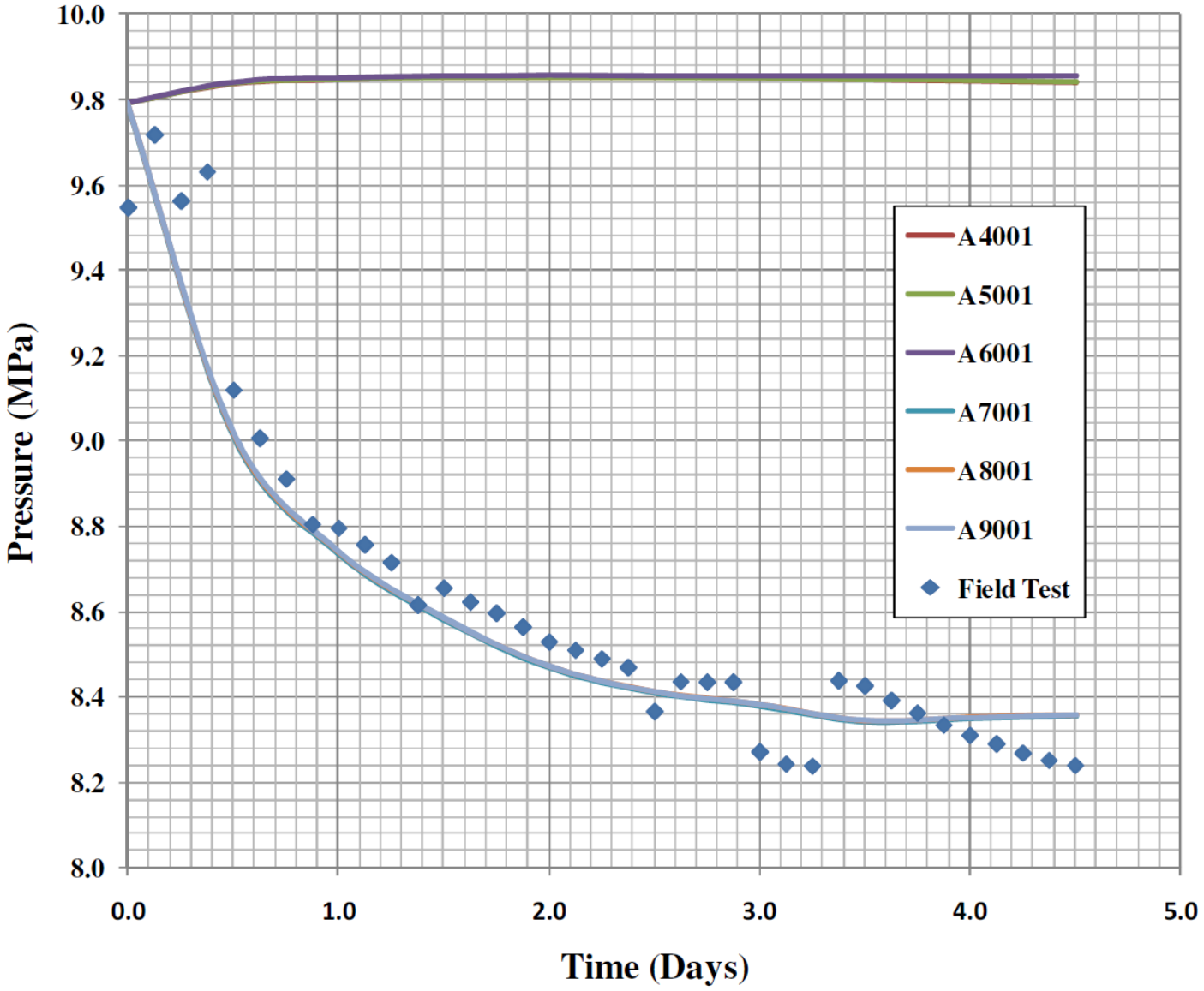




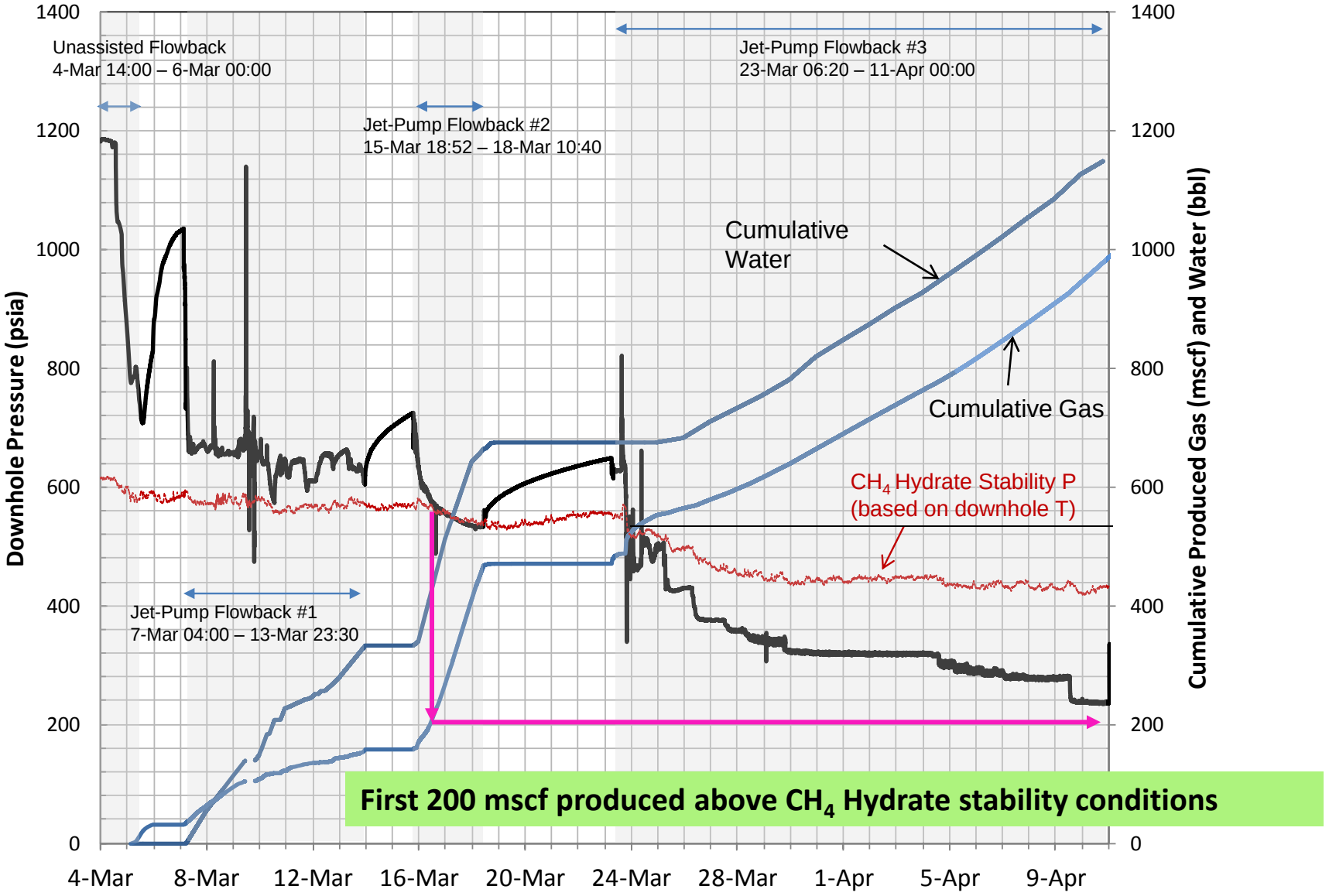
Post-Injection Period



Post-Injection Period

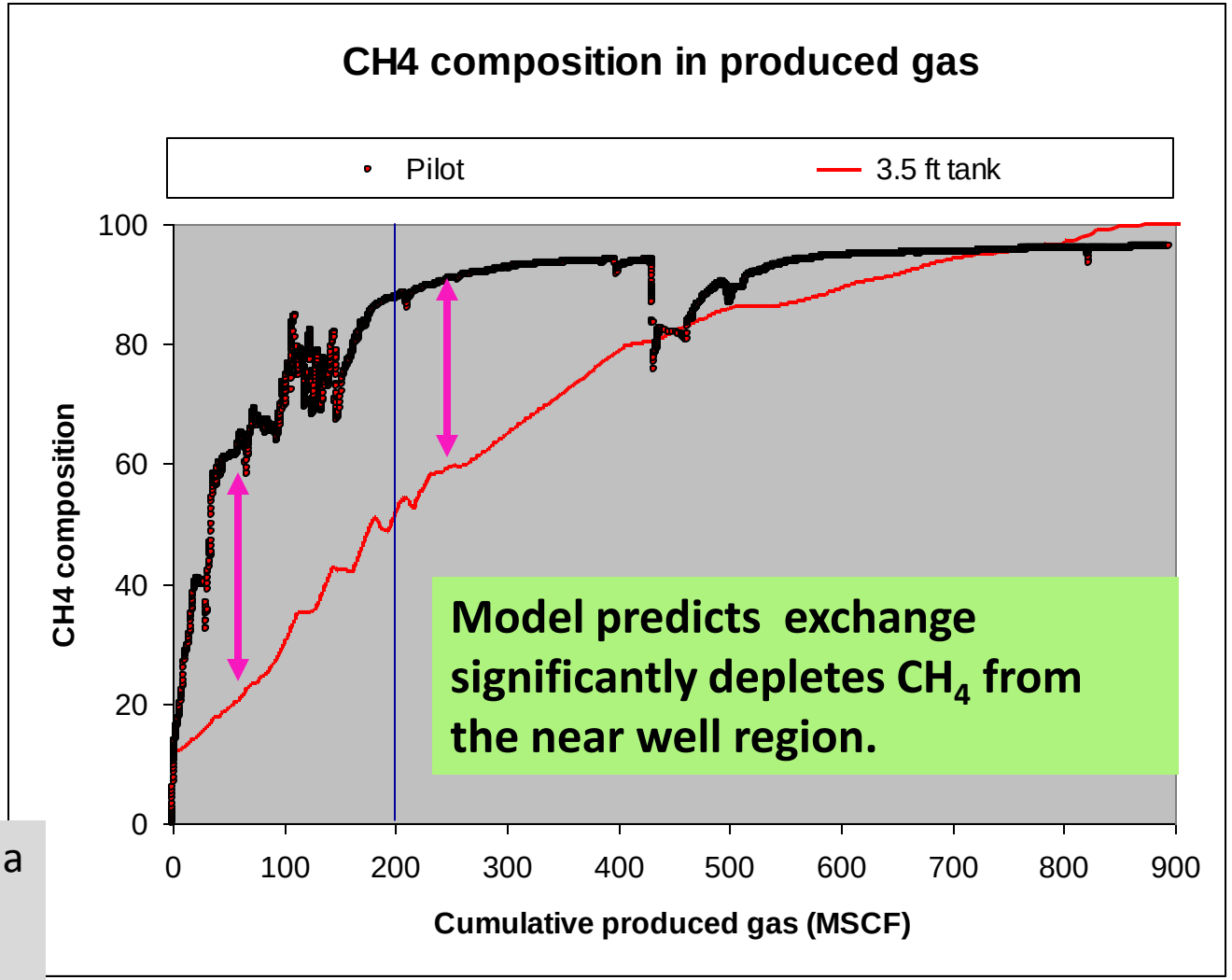


Production



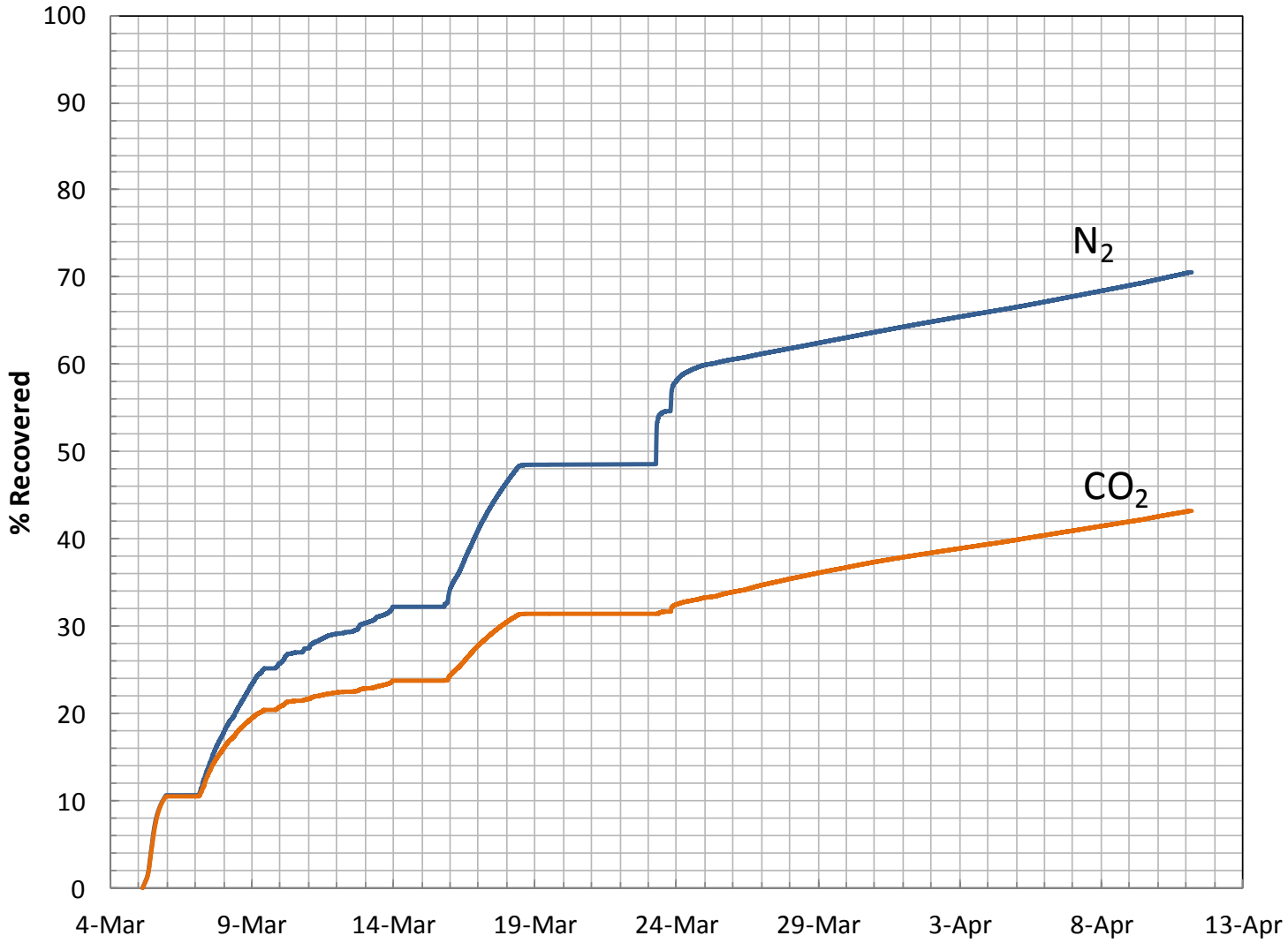
First 200 mscf produced above CH_4 Hydrate stability conditions

More CH_4 produced than Equilibrium Model predicts.



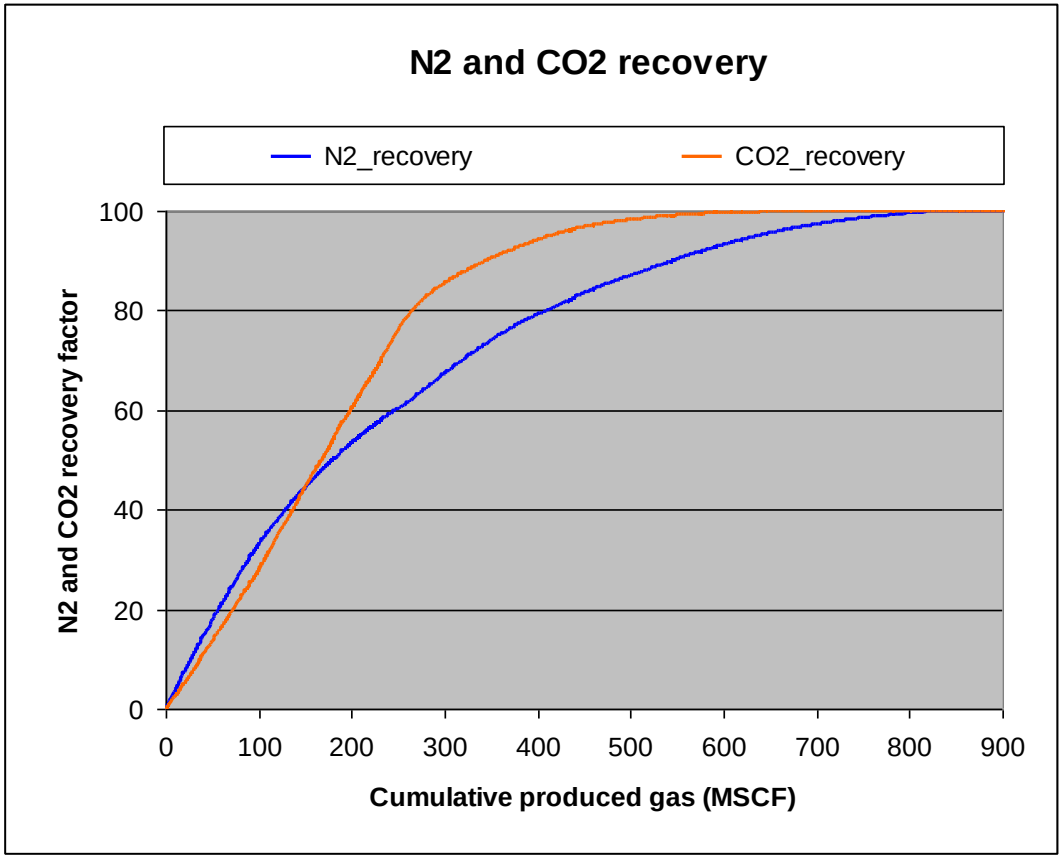
P_i = 1000 psia
S_{hi} = 65 %
T_i = 40.5 F

% Recovered based on Injected Amounts

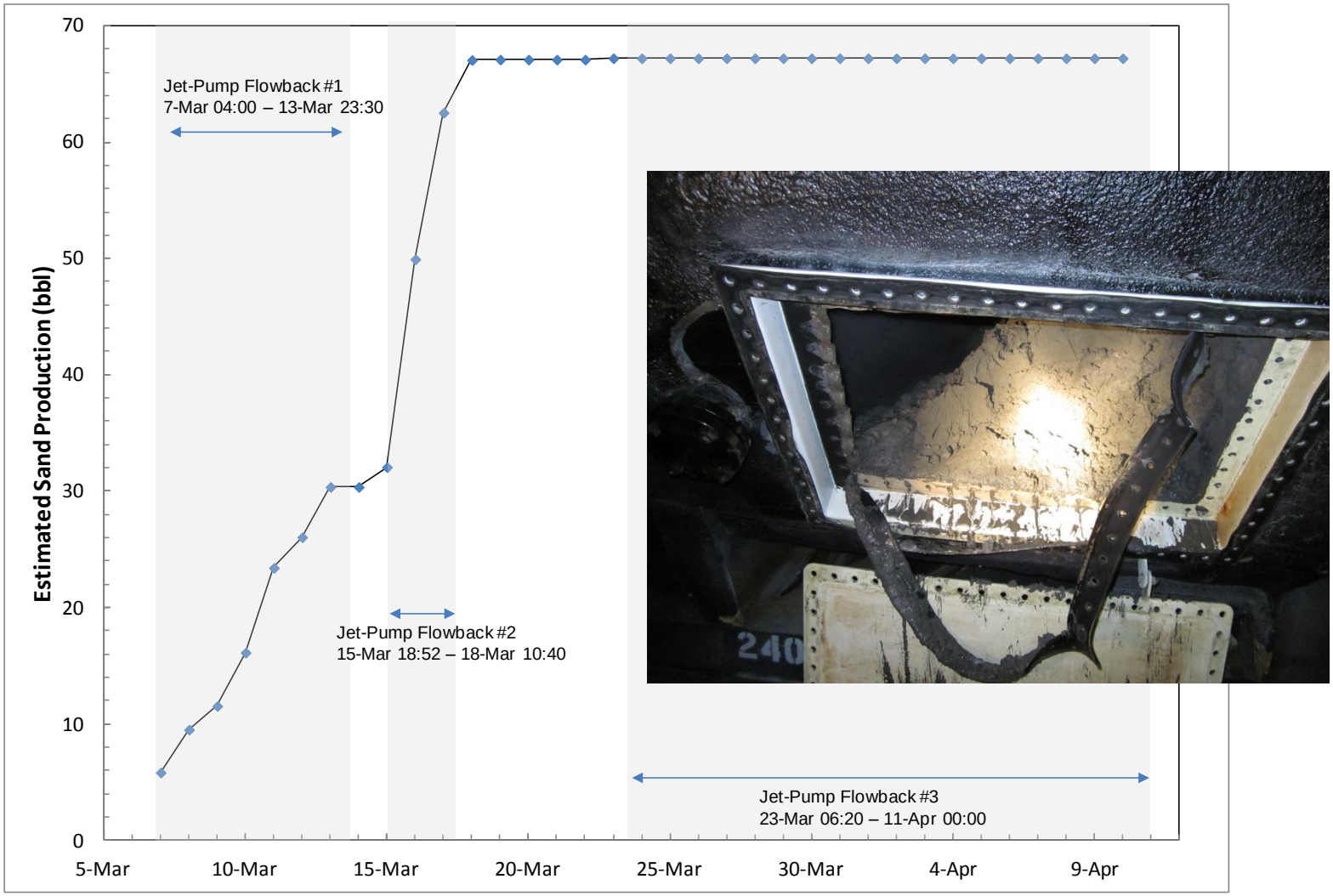


Observations: Field versus Model

- Not enough CH_4 from model
- Not enough water from model
- Temperature increase too high in model
- Recovery of N_2 to CO_2 reversed in model
- Examining potential mechanisms of gas production
  1. Dissociation in place w/o permeability enhancement
  2. Dissociation in place w/sand migration + permeability enhancement
  3. Production of solid hydrate (< 200 µm) and subsequent dissociation in wellbore above the jetpump when contacted with warm power fluid



Sand Production



Mechanism 2 – Experience at Mallik

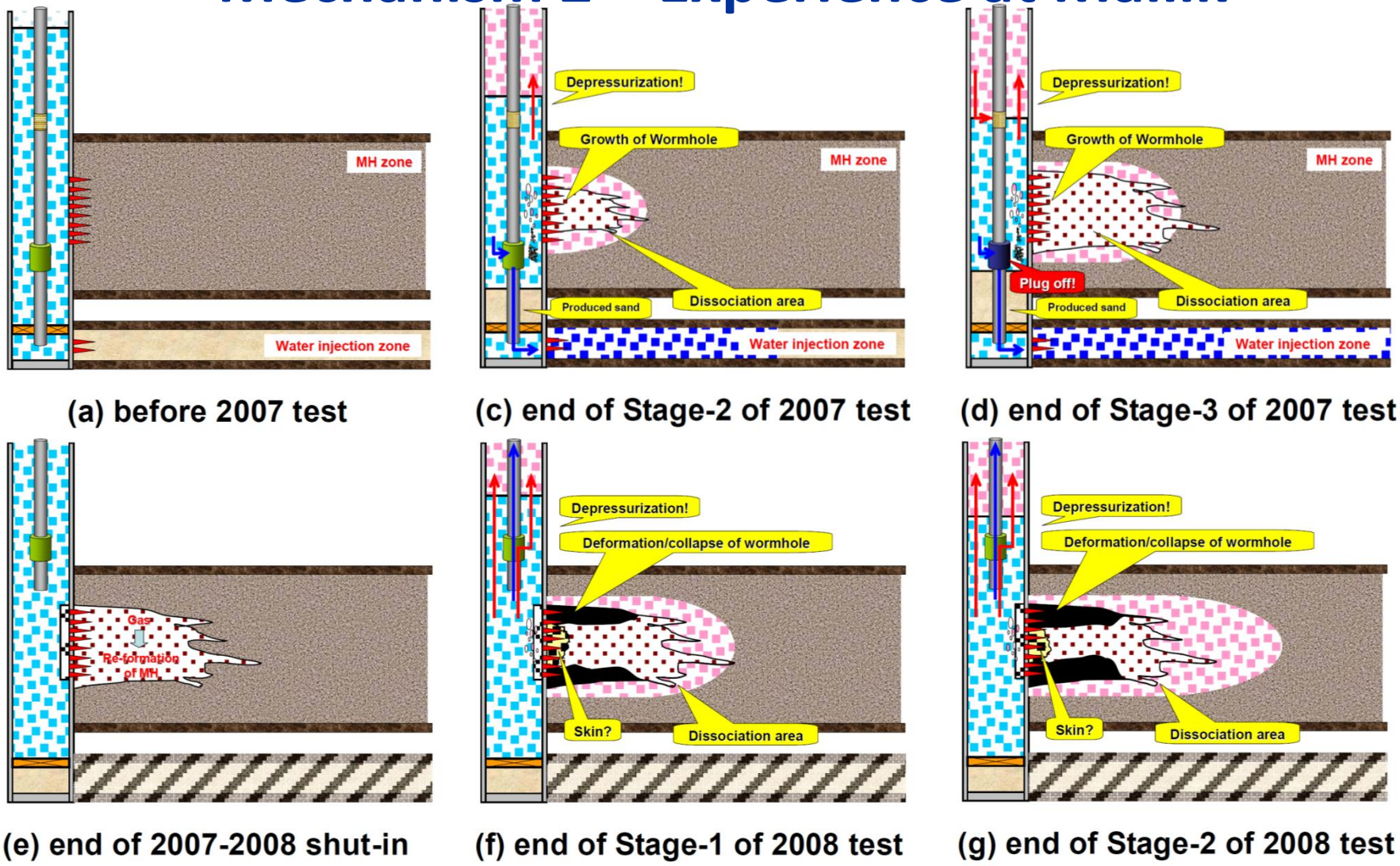


Figure 17 Schemata of reservoir performances through 2007 and 2008 tests inferred from history matching simulation
From: Kurihara, et al., Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21, 2011

Mechanism 2

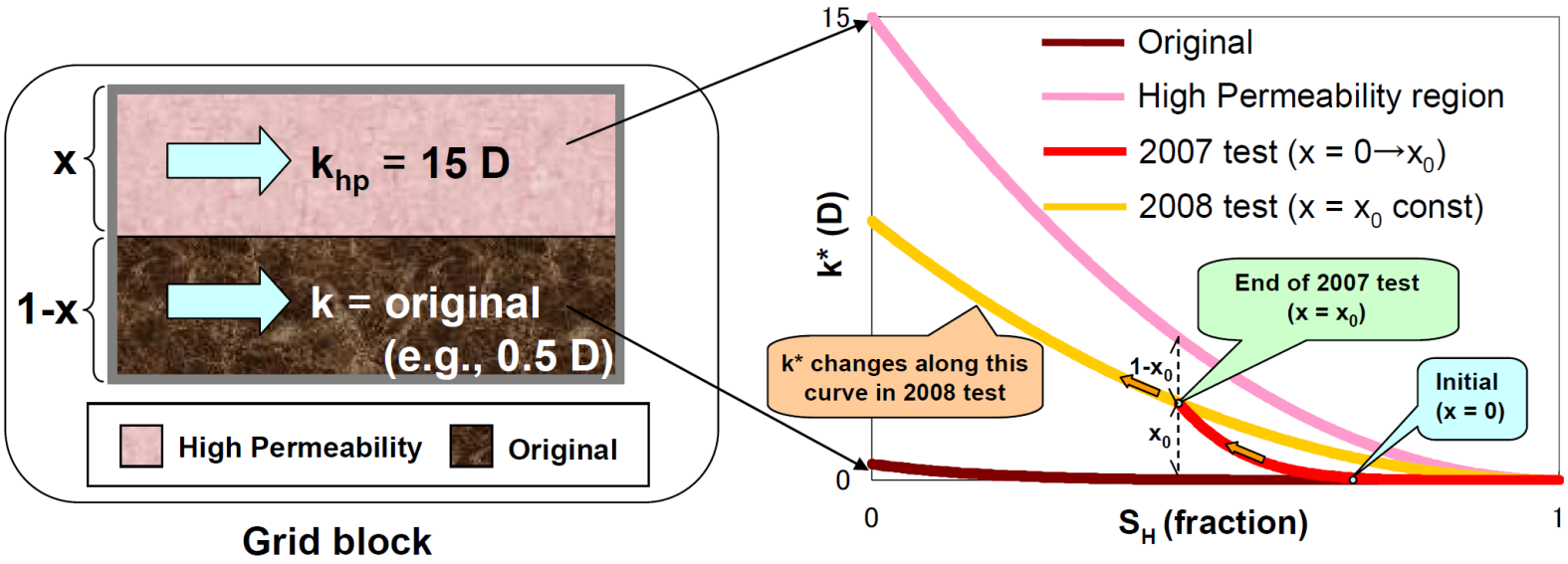


Figure 11 Concept expressing overall grid block permeability as a function of MH saturation with growth of high permeability conduits

$$k^* = xk_{hp}(1-S_h)^2 + (1-x)k_o(1-S_h)^N$$

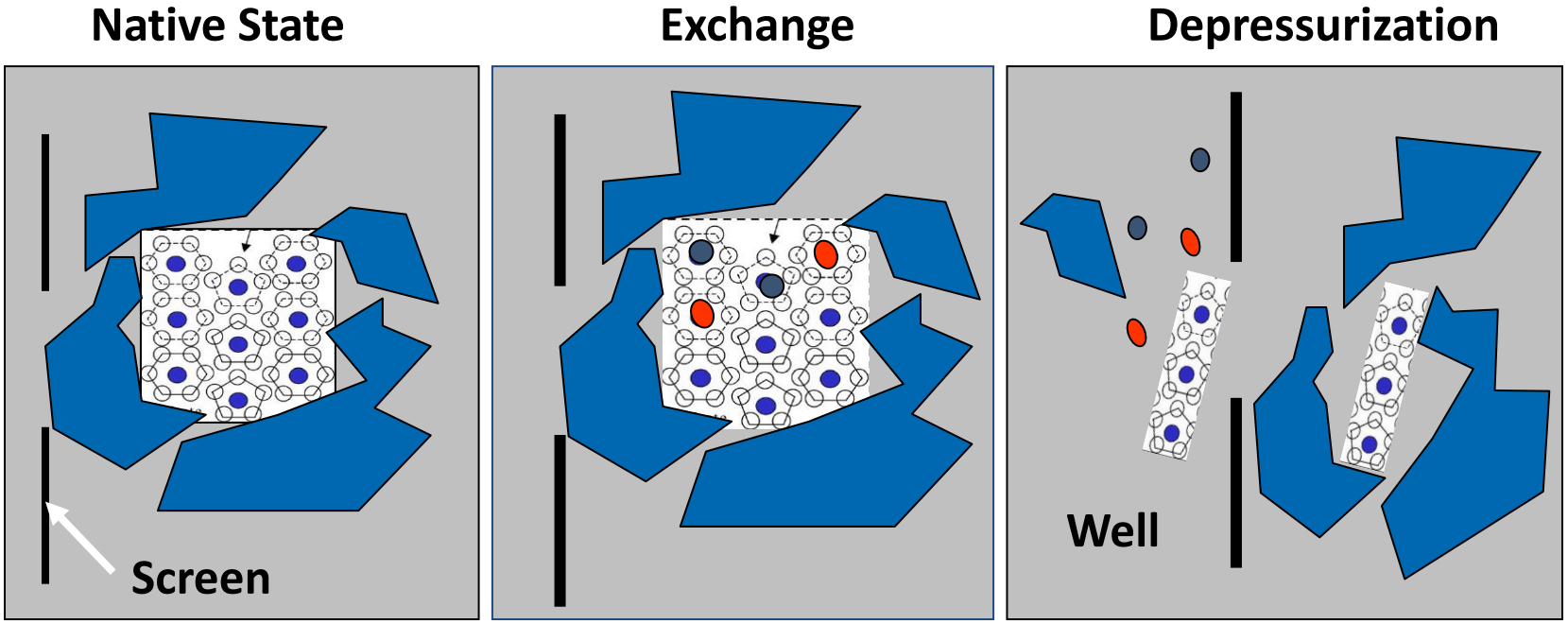
$$k_{eg} = k^* k_{rg}$$

$$k_{ew} = k^* k_{rw},$$

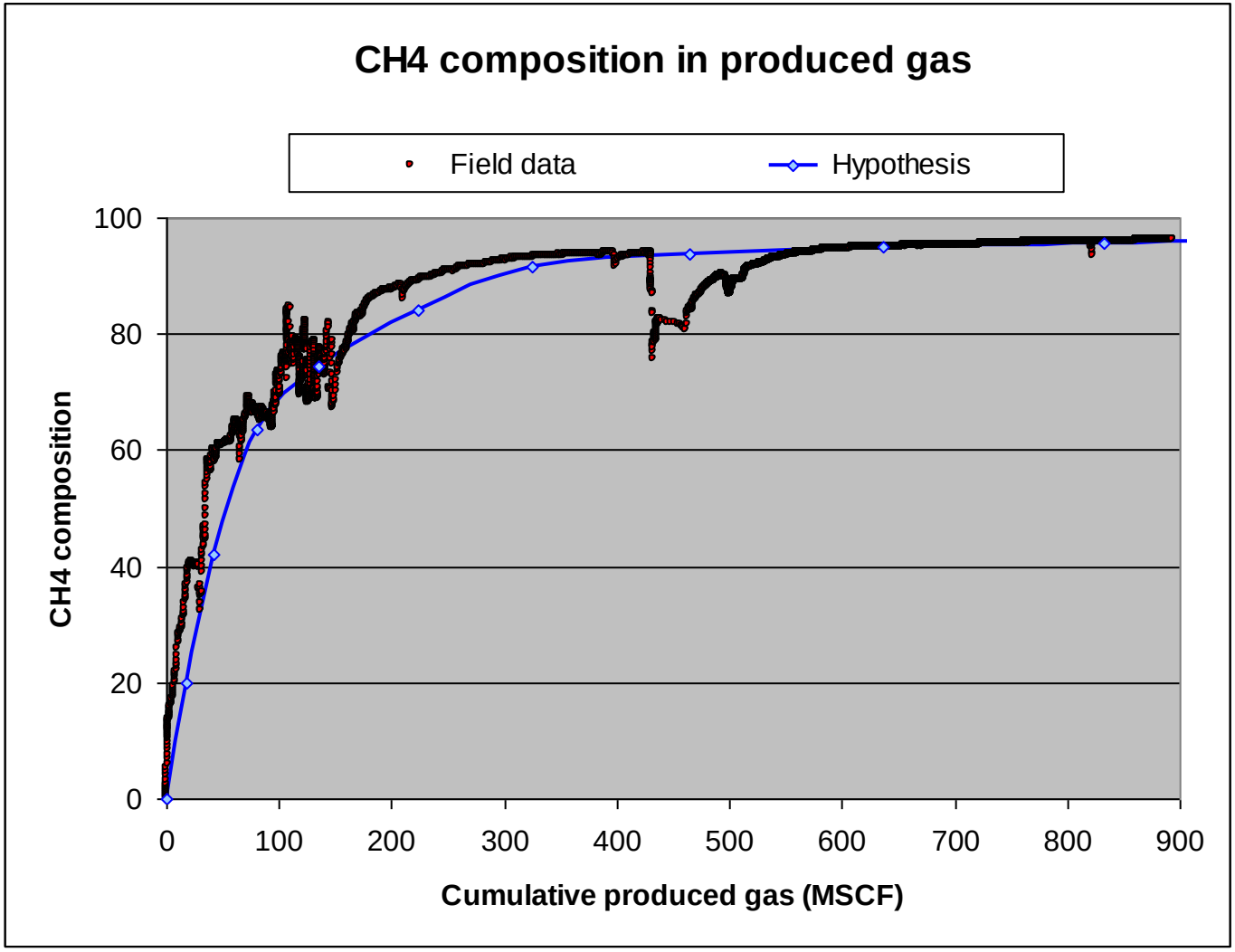
From: Kurihara, et al., Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21, 2011

Mechanism 3: Solid CH_4 – Hydrate produced?

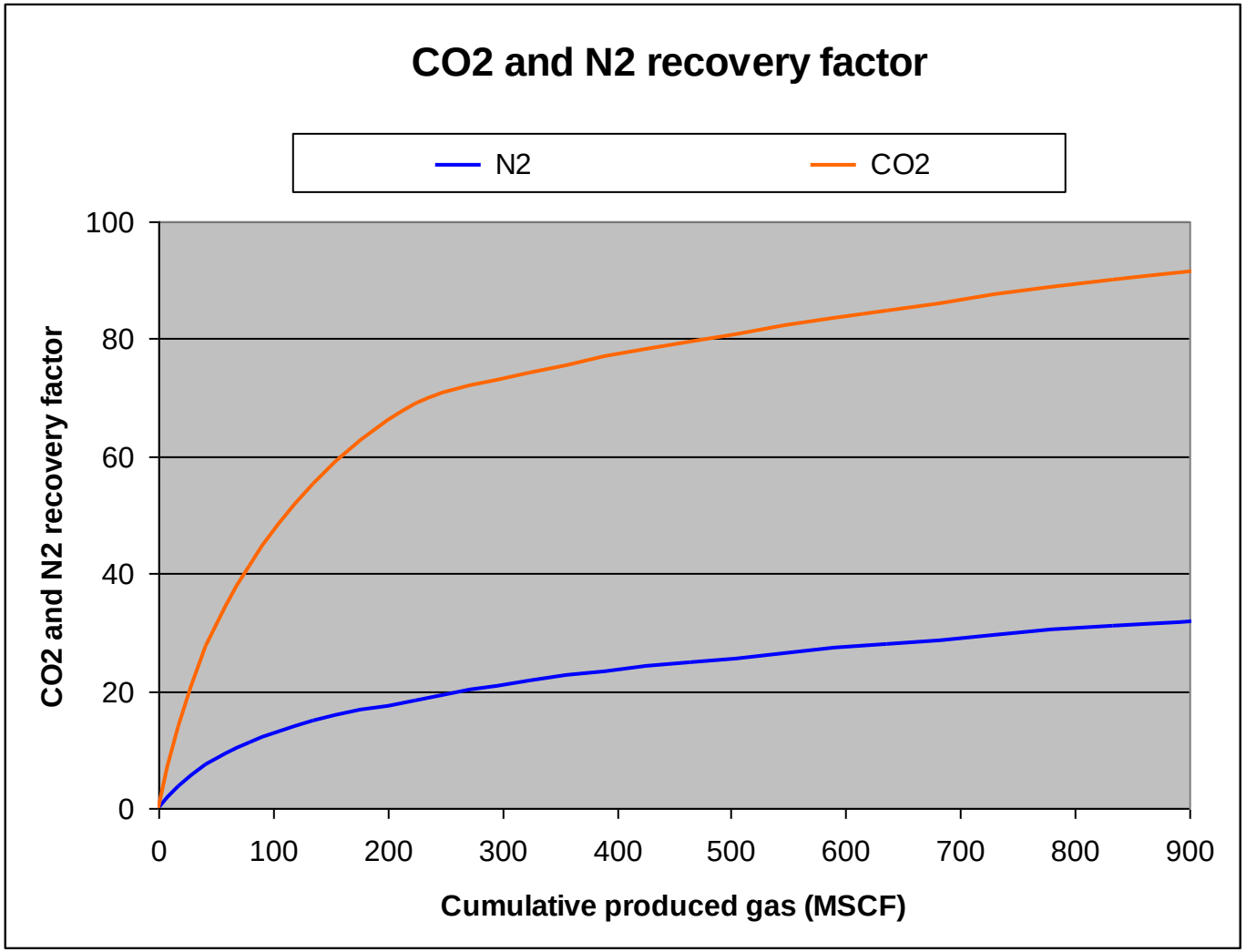
- Largest source of CH_4 & water = CH_4 Hydrate
- Solids (sand) were produced



Mechanism 3: CTC Model Solids Recombination – CH_4 Match

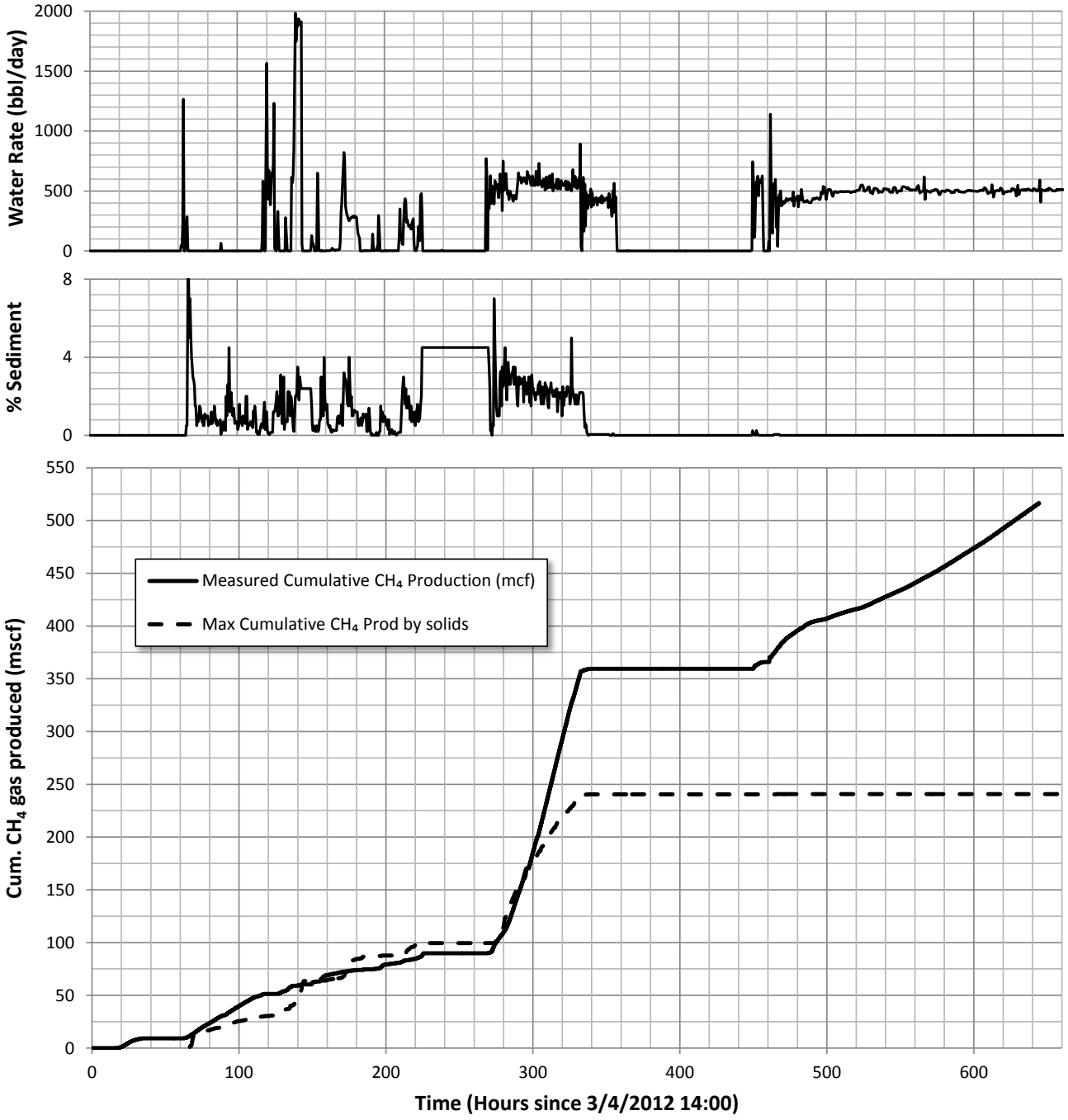


Mechanism 3: CTC Model Solids Recombination – Recovery



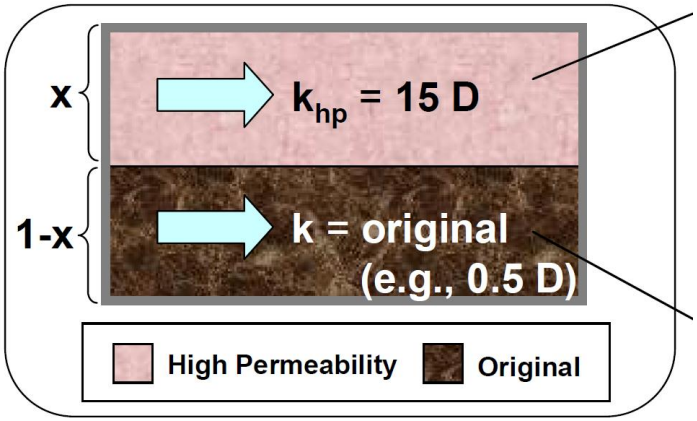
Mechanism 3

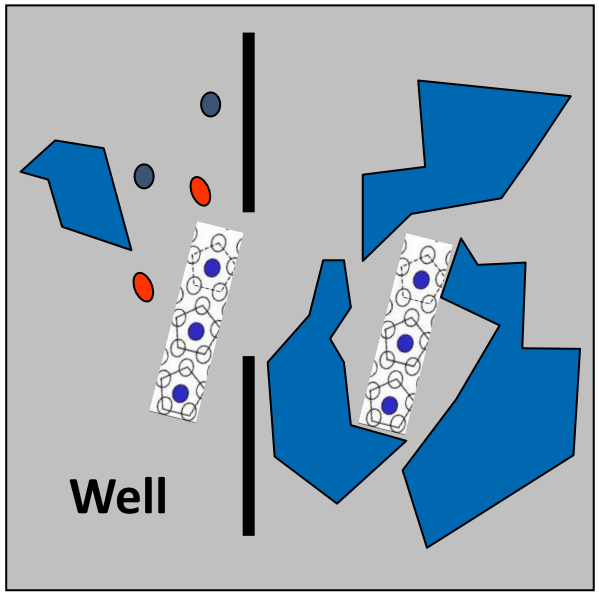
- **Method**
  - Use EXPRO water rate and %Sed measurements
  - Scale sediment rates to match observed cumulative sand production
- **Worst-case Assumptions**
  - All sand produced had associated CH_4 hydrate that was produced
  - S_H values from CMR log
- **Gives upper limit to CH_4 from solids**



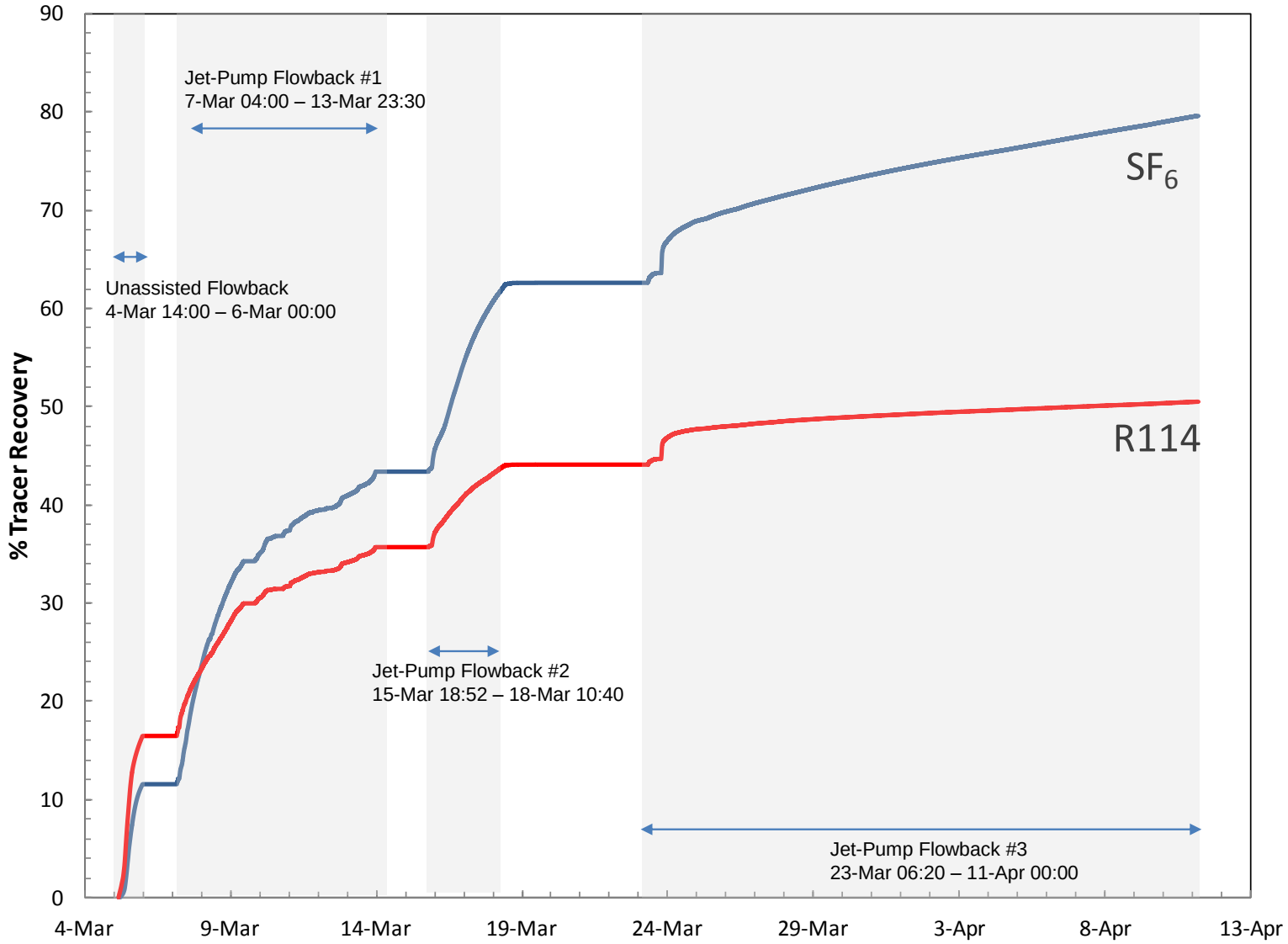
Field trial likely a combination of mechanisms

- **Mechanism 2**
  - Dissociation in place w/sand migration + permeability enhancement
- **Mechanism 3**
  - Production of solid hydrate (< 200 µm) and subsequent dissociation in wellbore above the jetpump when contacted with warm power fluid
- **Reservoir heterogeneity**

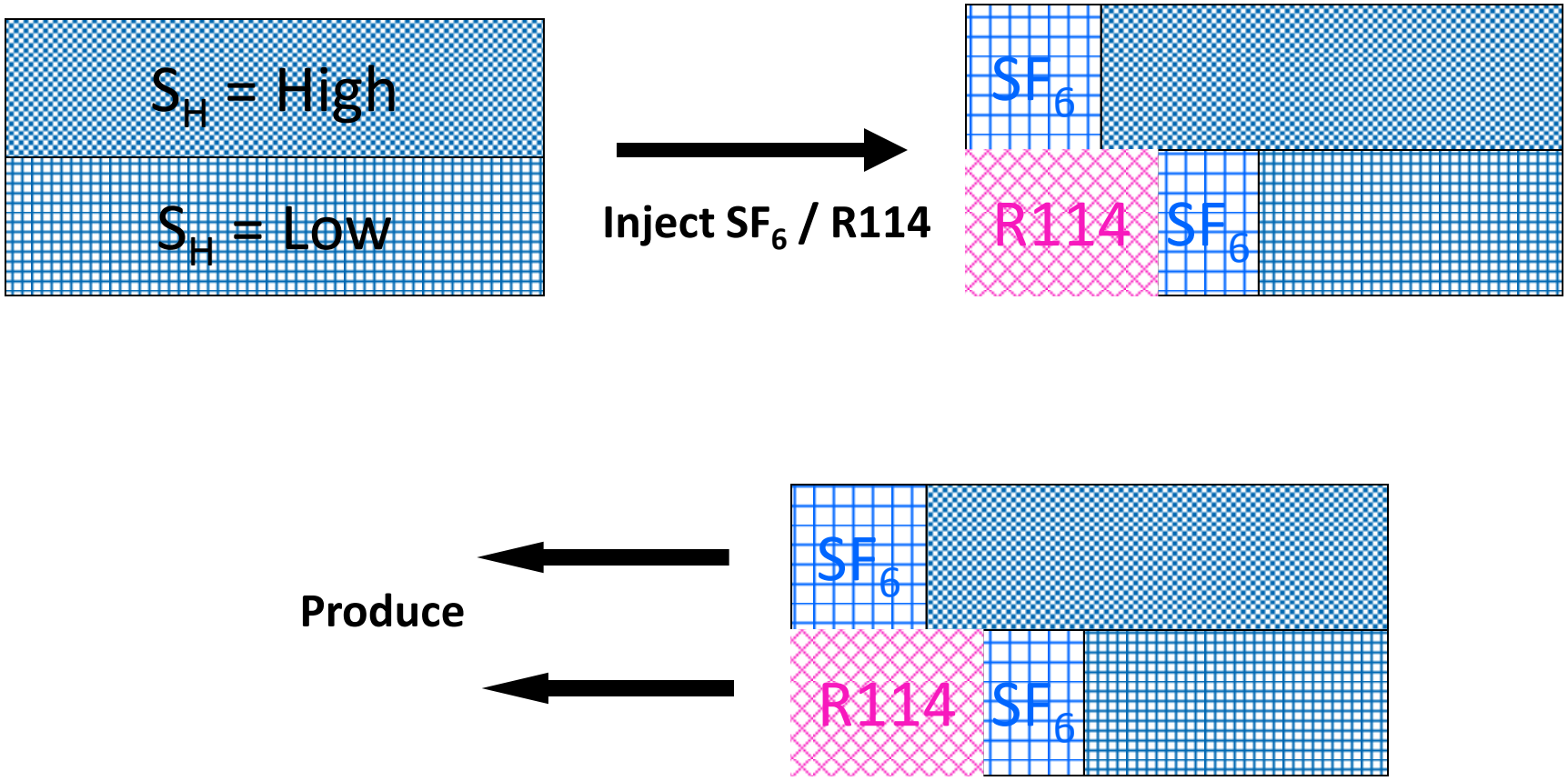




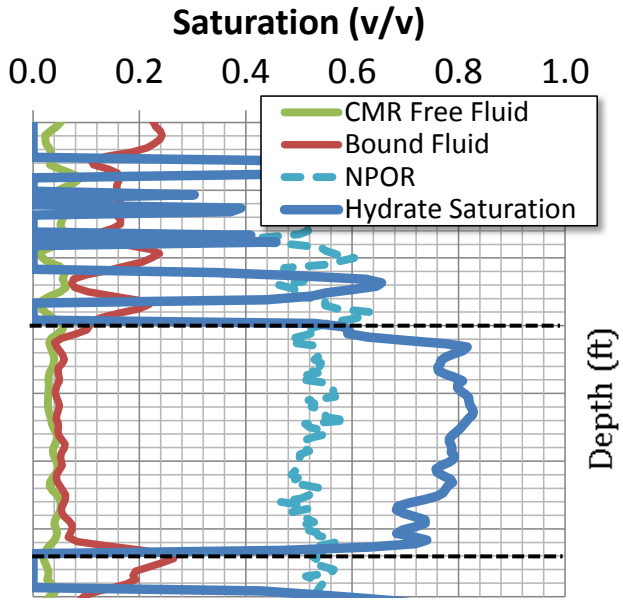
Tracer … Argument for Heterogeneity?

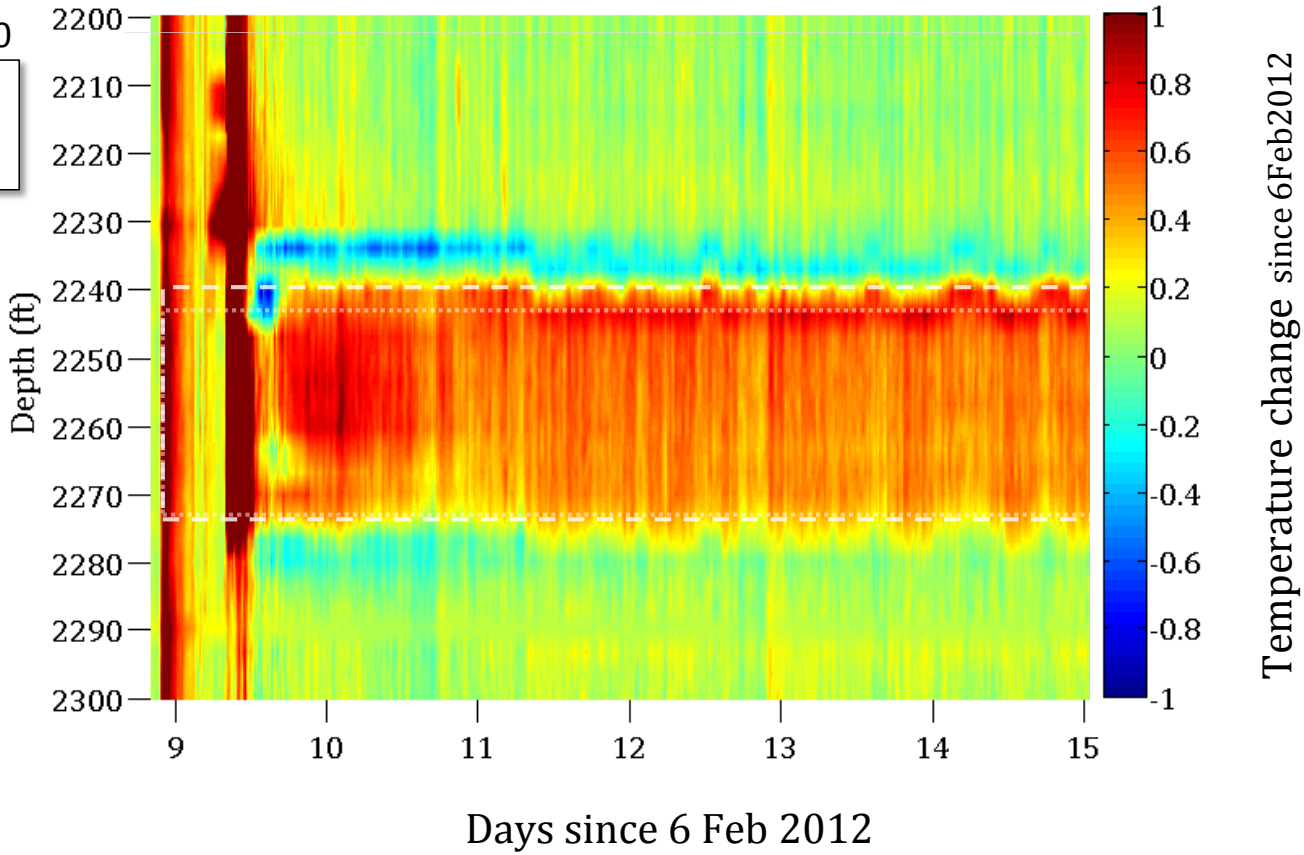


Heterogeneous Injection / Production

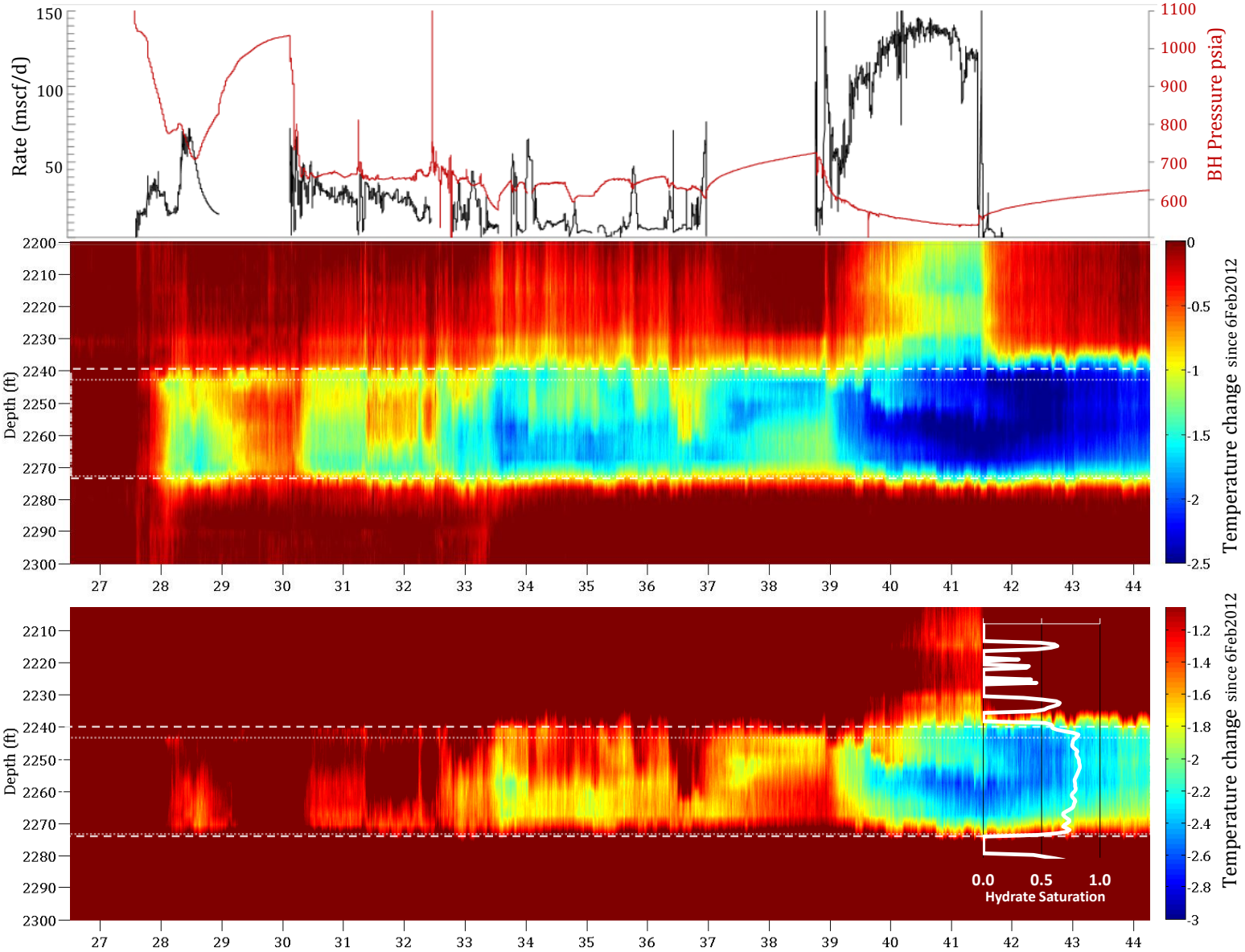


Heterogeneous Injection



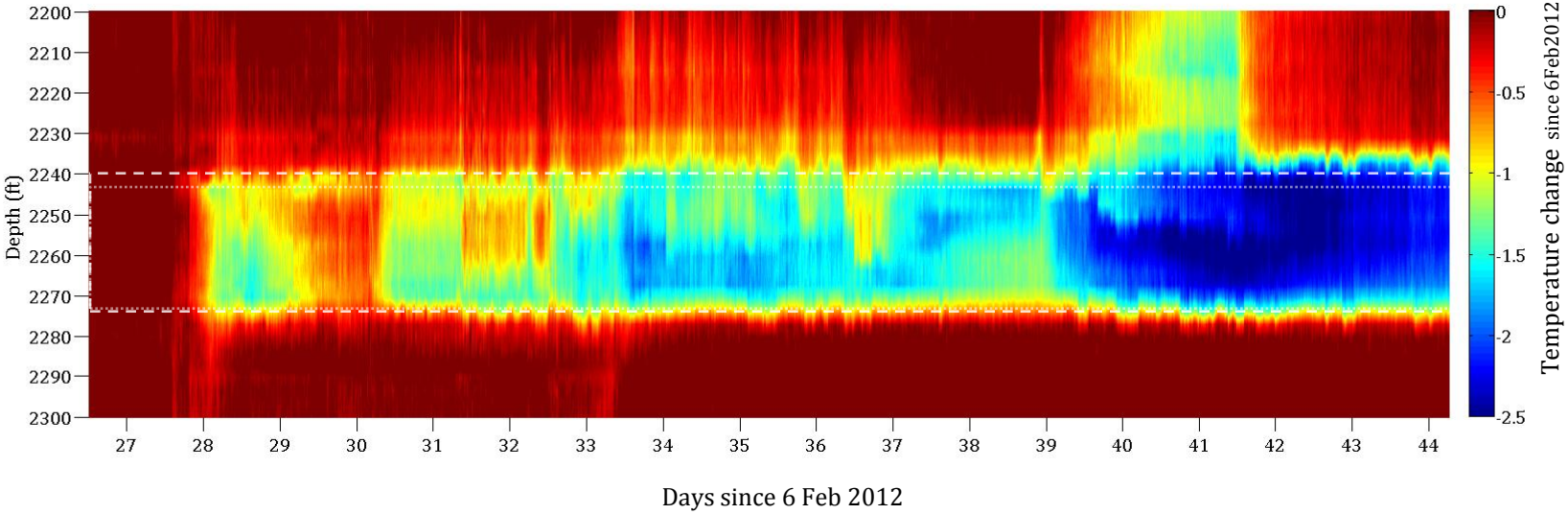


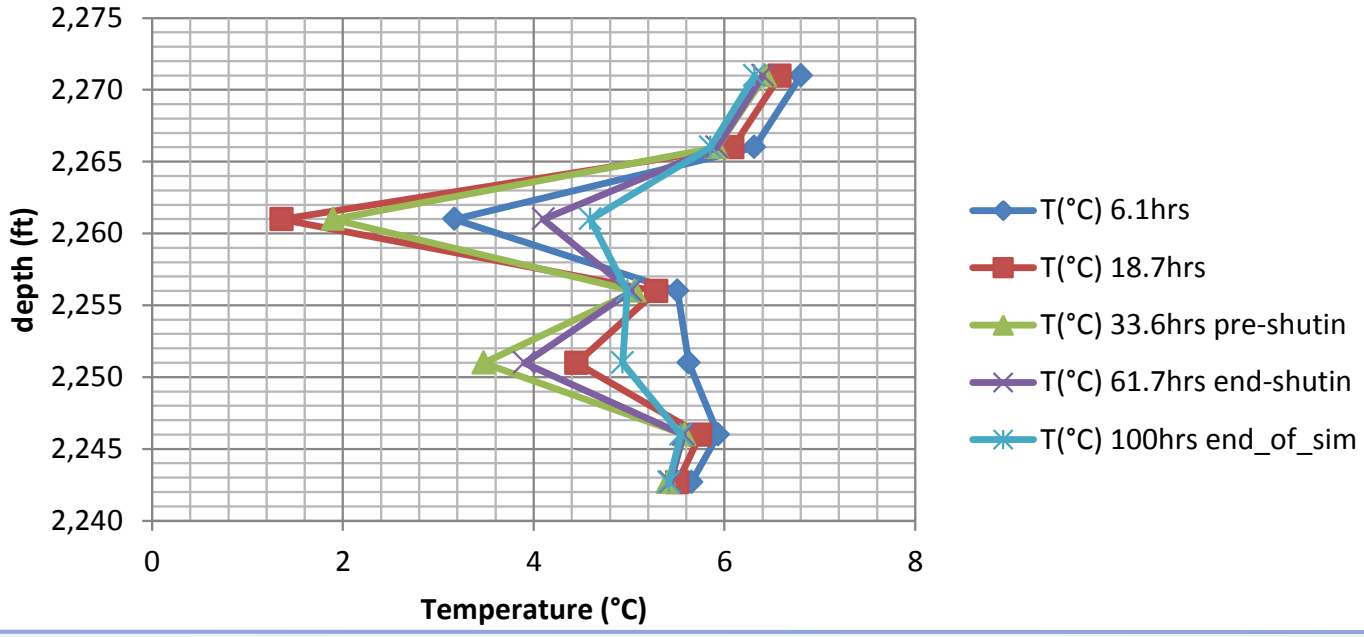
Flowback - Production Period #1



Days since 6 Feb 2012

Production Period #1

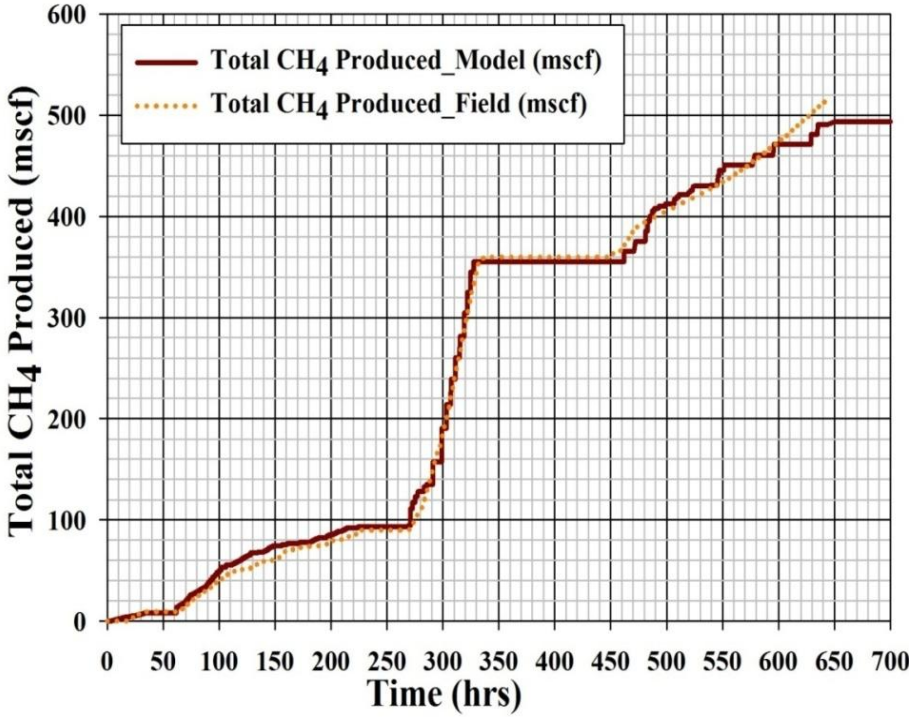


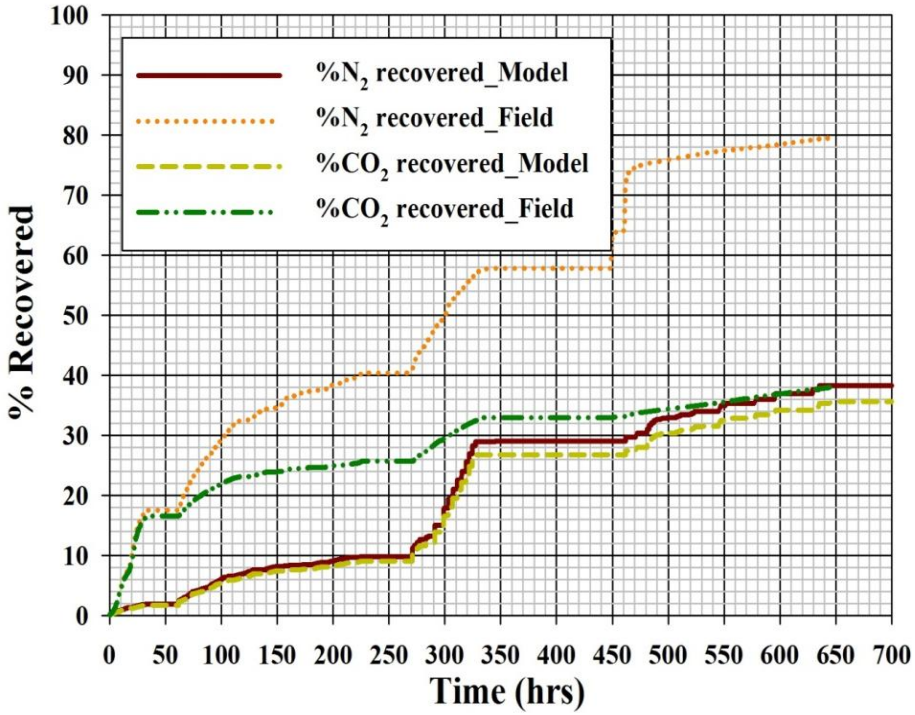


Production Simulations

Production

- Production phase is modeled by maintaining fixed-state boundary as aqueous phase at the bottom-hole pressure.
- Still attempting to match sand production and each gas rate (with recovery factors)





Tentative Conclusions

- Demonstrated injection of CO_2 mixture into water filled hydrate reservoir
  - Possibly some injection out-of-zone
- Confirmed mixture / CH_4-Hydrate Exchange
  - CH4 produced above CH4-hydrate stability pressure
  - Produced CO_2 : N_2 ratios altered from injectant value
  - Injectivity decline consistent w hydrate exchange
- Low BHP are achievable during depressurization
  - Icing not observed @ 250 psi BHP
- Heterogeneous injection / production observed (DTS)
- Temperature record consistent w hydrate association / dissociation during injection / production cycles

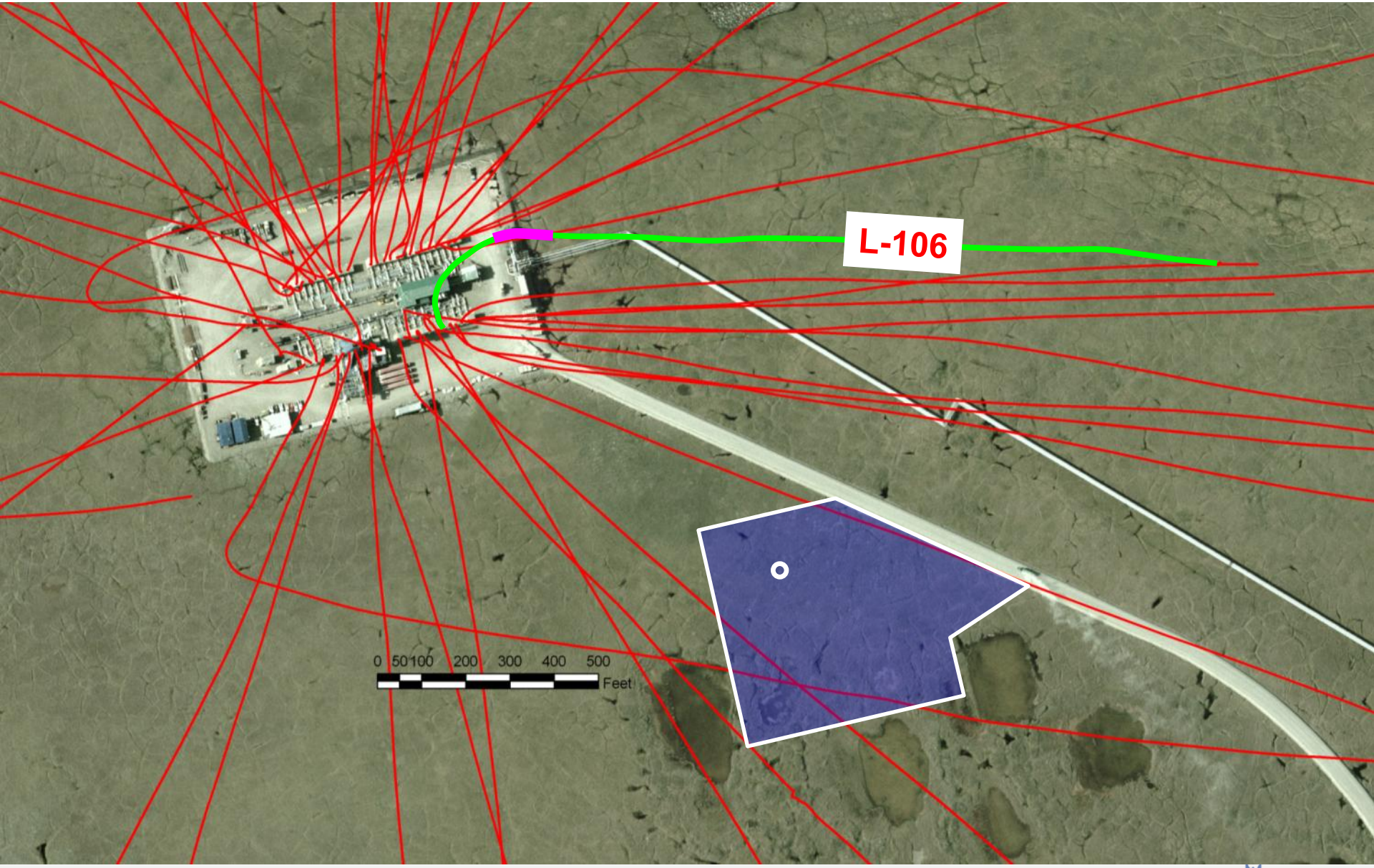
Going Forward

- **Datasets and ConocoPhillips project reports can be downloaded from the NETL website.**
  - http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/rd-program/ANSWell/co2_ch4exchange.html
  - google “ignik sikumi” or see the announcement in the latest *Fire in the Ice*
- **Organizing a problem for the Code Comparison Project on the Ignik Sikumi Results**
- **DOE has previously facilitated creation of Special Volumes in peer-reviewed journals to consolidate reporting**

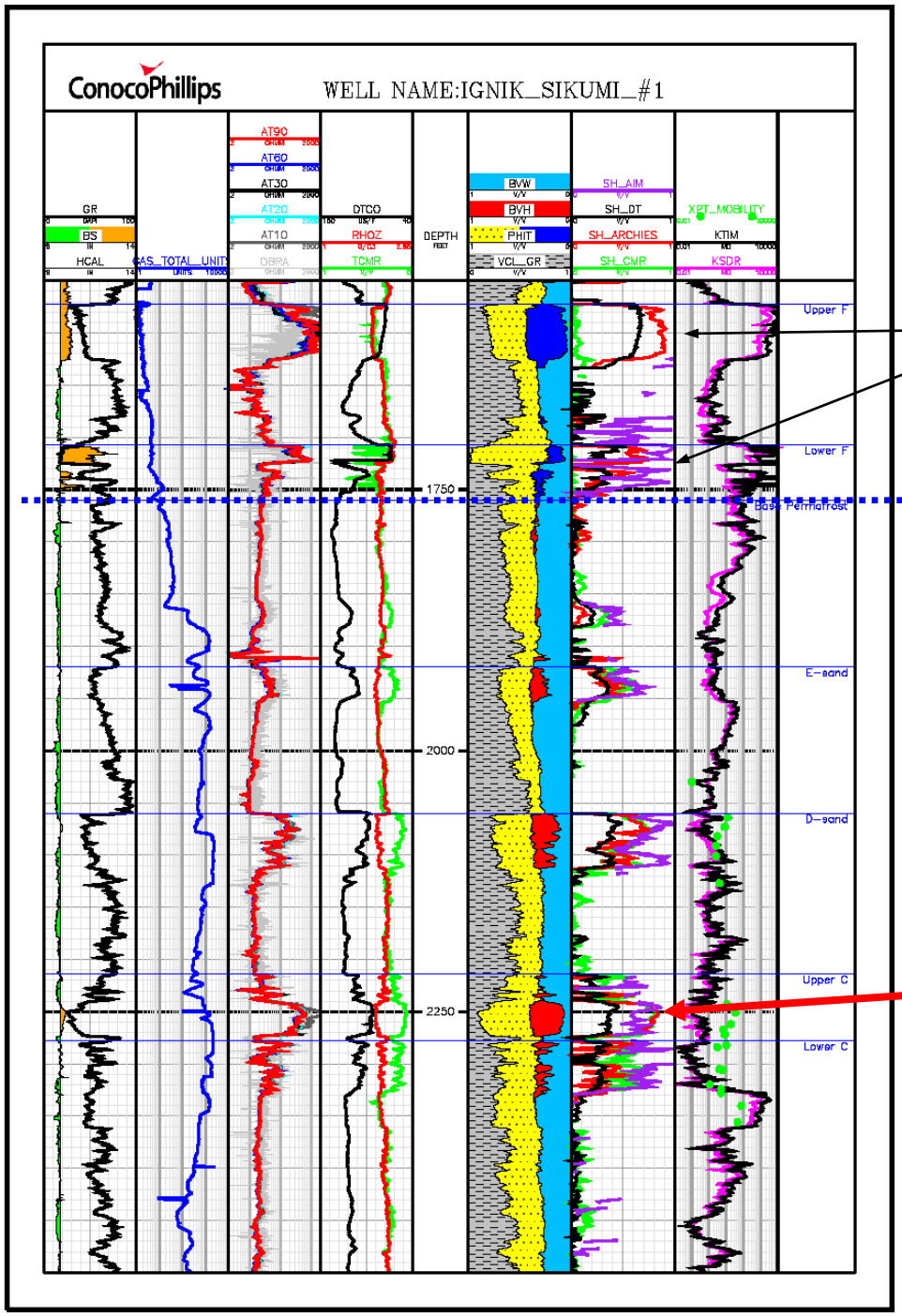

Questions?

Backup Slides – do not print

CPAI - Iġnik Sikumi #1 and PBU L-pad



Iġnik Sikumi #1



Sagavanirktok “F Sand:” Ice-filled

base permafrost

“E sand:” 31ft hydrate

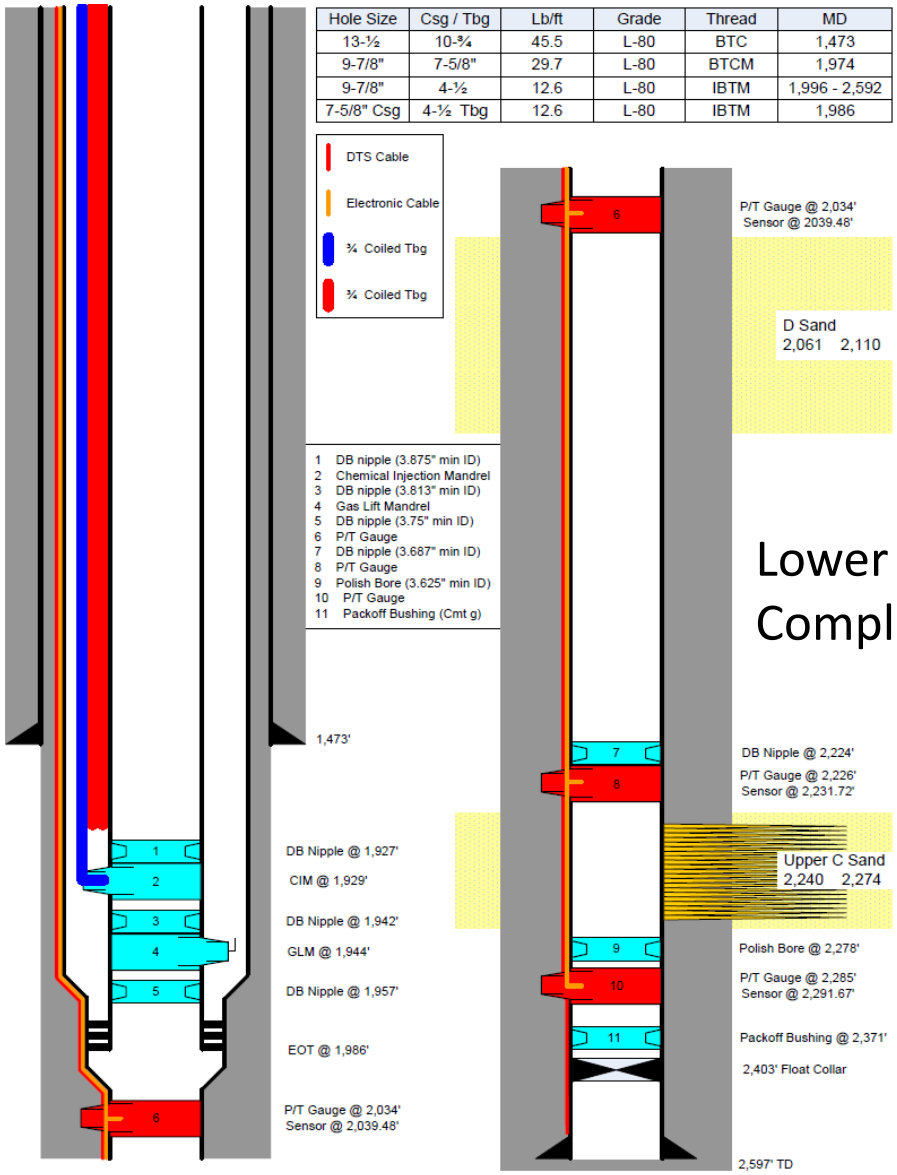
“D sand:” 49ft hydrate

Target: Upper C Sand

“C sand:” 67ft hydrate

Wellbore Construction

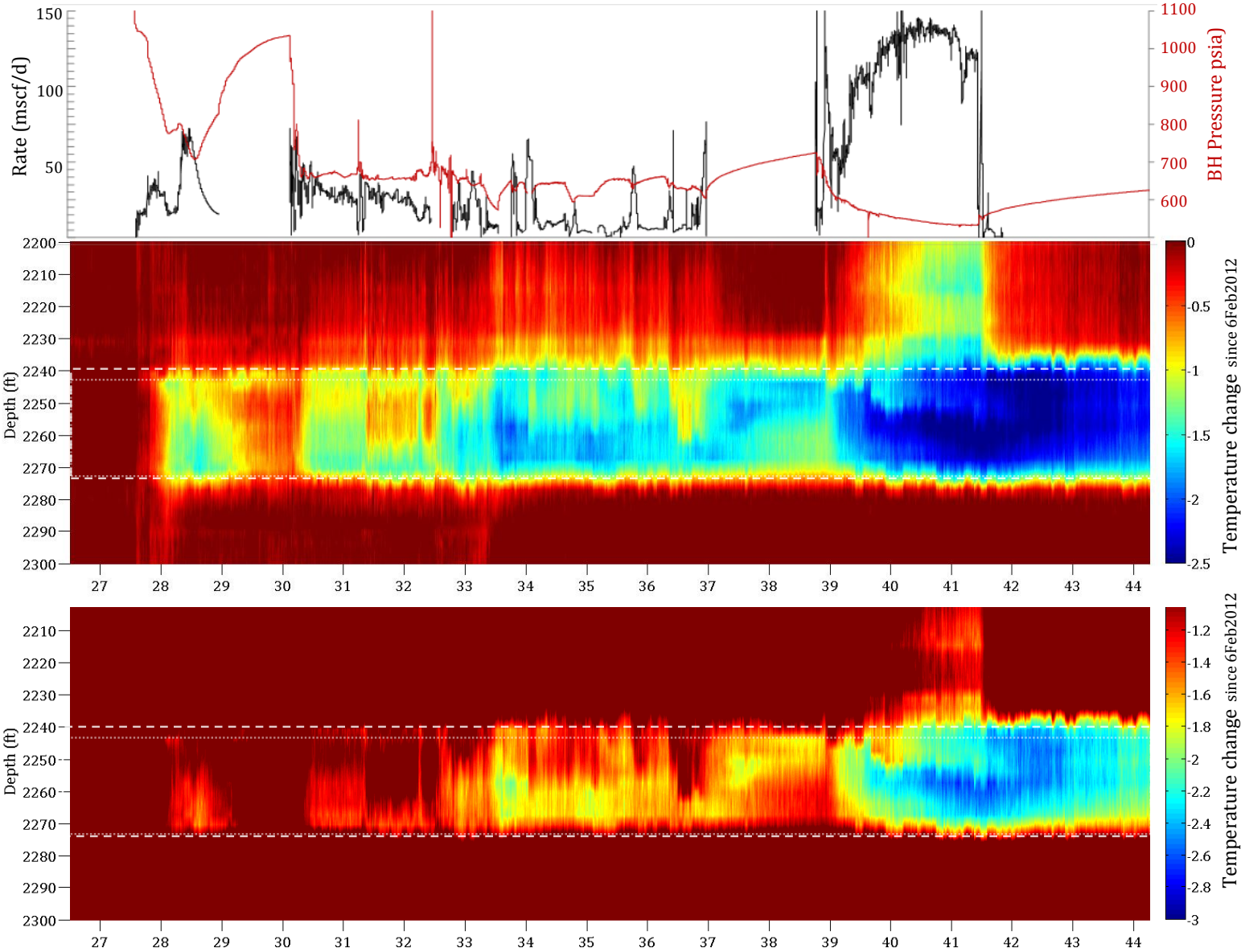
Hole Size	Csg / Tbg	Lb/ft	Grade	Thread	MD
13-½	10-¾	45.5	L-80	BTC	1,473
9-7/8"	7-5/8"	29.7	L-80	BTCM	1,974
9-7/8"	4-½	12.6	L-80	IBTM	1,996 - 2,592
7-5/8" Csg	4-½ Tbg	12.6	L-80	IBTM	1,986



Upper Completion

Lower Completion

Flowback - Production Period #1

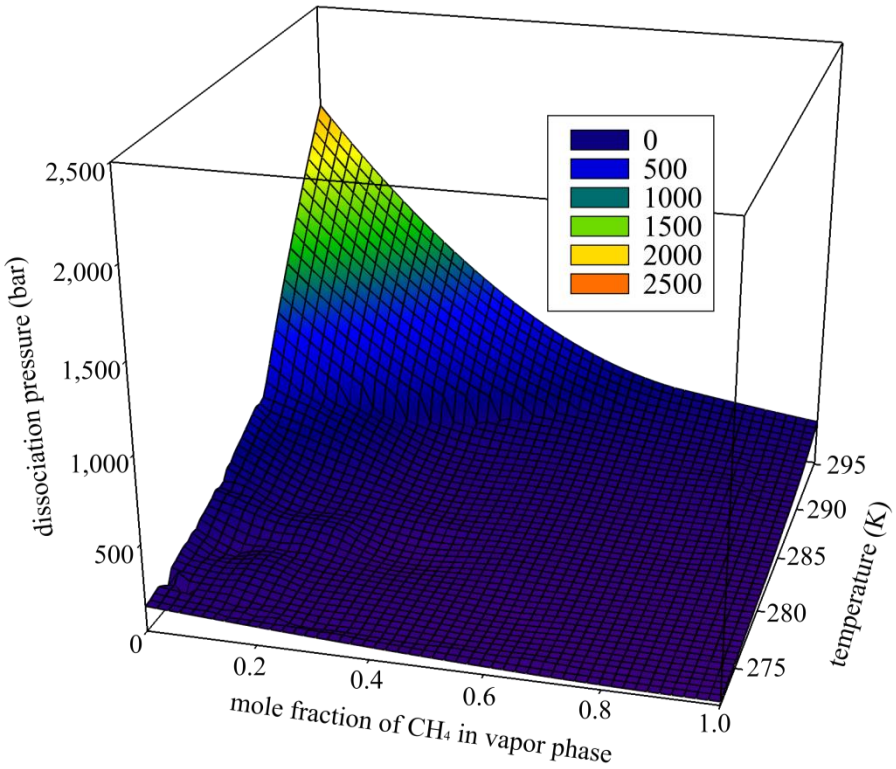


Ternary Hydrate Modeling

- The phase equilibrium data for a three-component (CH_4-CO_2-N_2) gas hydrate are incorporated using tri-linear interpolation, where in the code can interpolate data from a table containing stability pressure, temperature and composition of the hydrate phase
  - Based on predictions using our statistical mechanics model that has been validated against experimental data for 1-, 2-, and 3-component gas mixtures with low error
  - Two data files are incorporated into

    $T_{eq} = f(P, y_1, y_2)$ and $P_{eq} = f(T, y_1, y_2)$

    where T is temperature (C), P is pressure (MPa), y_1 is CH_4 composition in gas phase and y_2 is CO_2 composition in gas phase (y_{N_2} is not independent)
- Two new primary variables for each phase state and two governing equations are added for the binary (CO_2) and ternary (N_2) gases
- Gas-Hydrate (GsH) system was added to consider the possibility of converting all available free water to form hydrate with injected gas



Prediction of stability pressure for the CH_4-CO_2 mixed hydrate system