550002

Hydrologic Setting and Hydrological Investigations of the Culebra

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Culebra Hydrology Conceptual Model Peer Review

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WIPP:1.4.2.3:PER:QAL:RECERT:549534

Outline

- Hydrologic setting
- Well network
- Hydraulic testing
- Monitoring
- Modeling of water-level rise
- Conceptual Model

Hydrologic Setting

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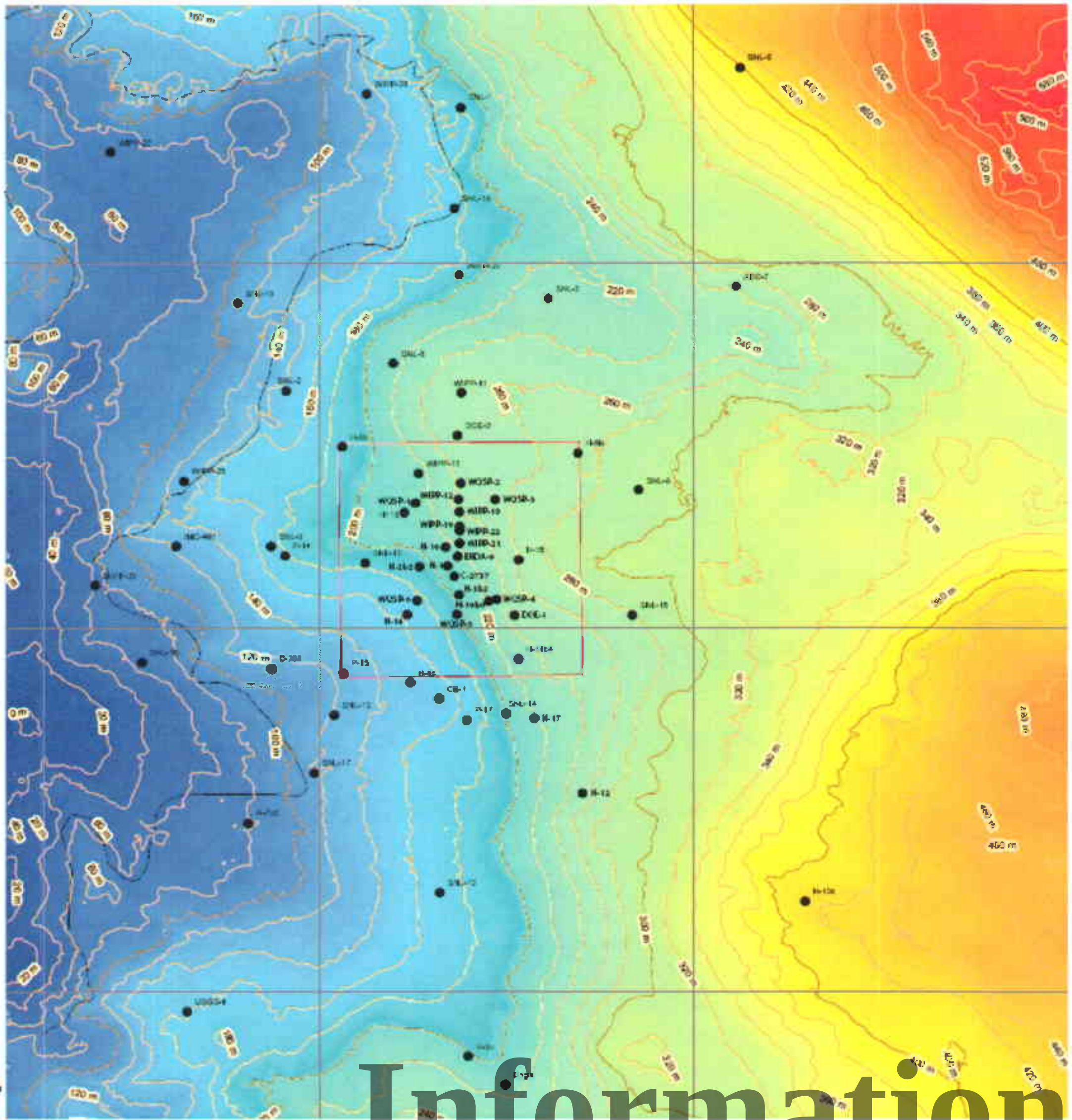
Culebra Overburden Thickness



Culebra is 125-290 m bgs at WIPP site

Legend

Isopach

Value

Thick overburden: 600 meters

Thin overburden: 0 meters

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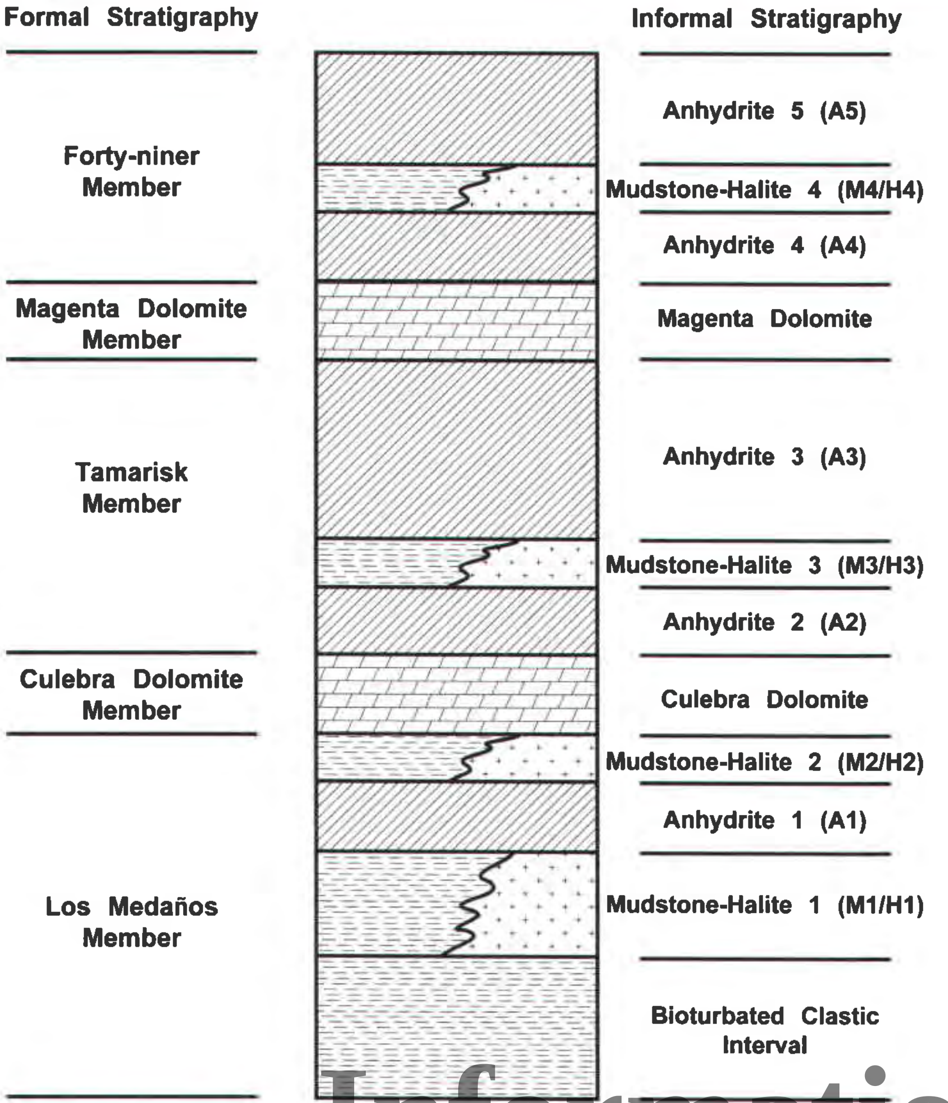
Rustler Stratigraphy



Culebra is confined by Los Medaños mudstone (M2) below and by Tamarisk anhydrite (A2) above

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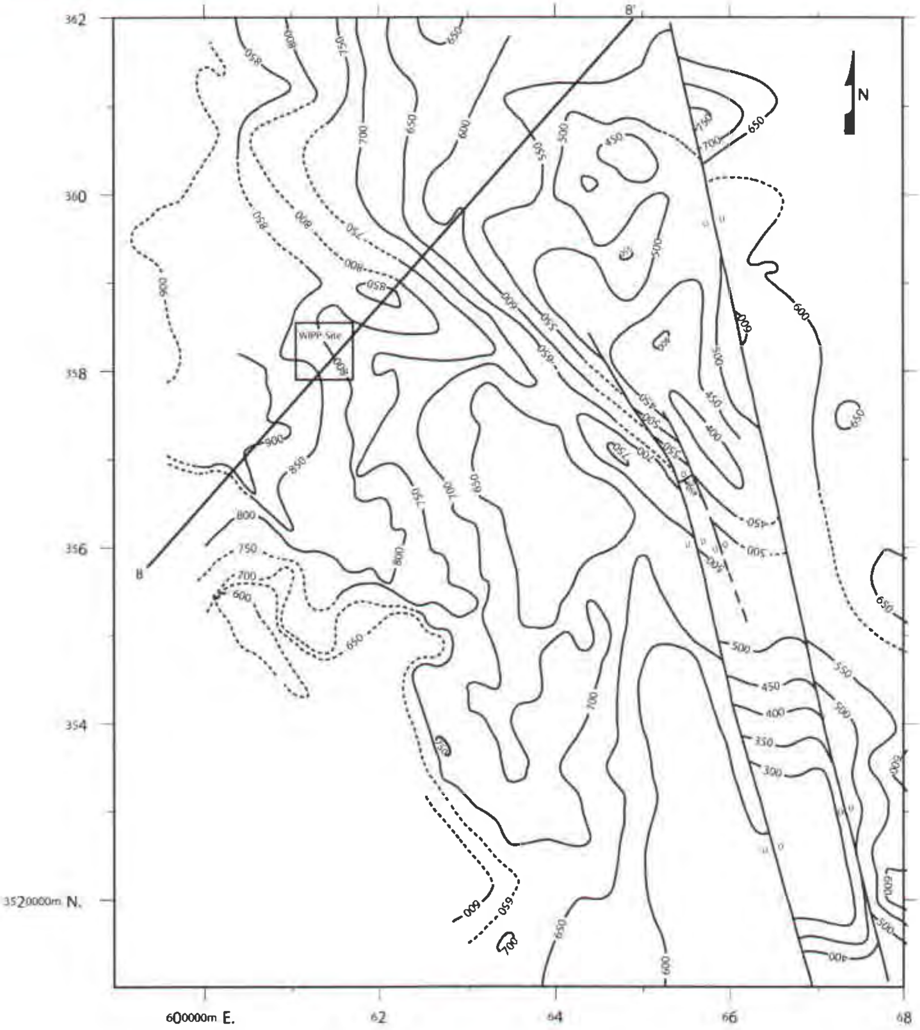
Culebra Structure Contour Map



U Upthrown Side of Fault
D Downthrown Side of Fault

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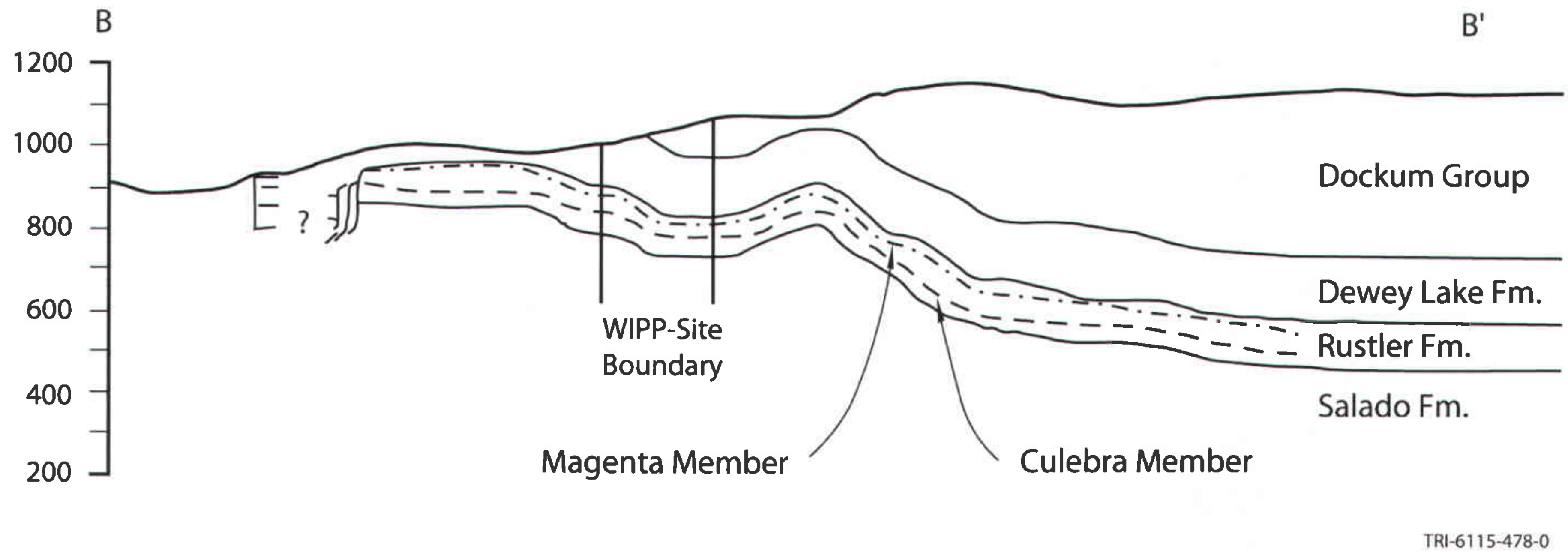
Cross Section Across the WIPP Site



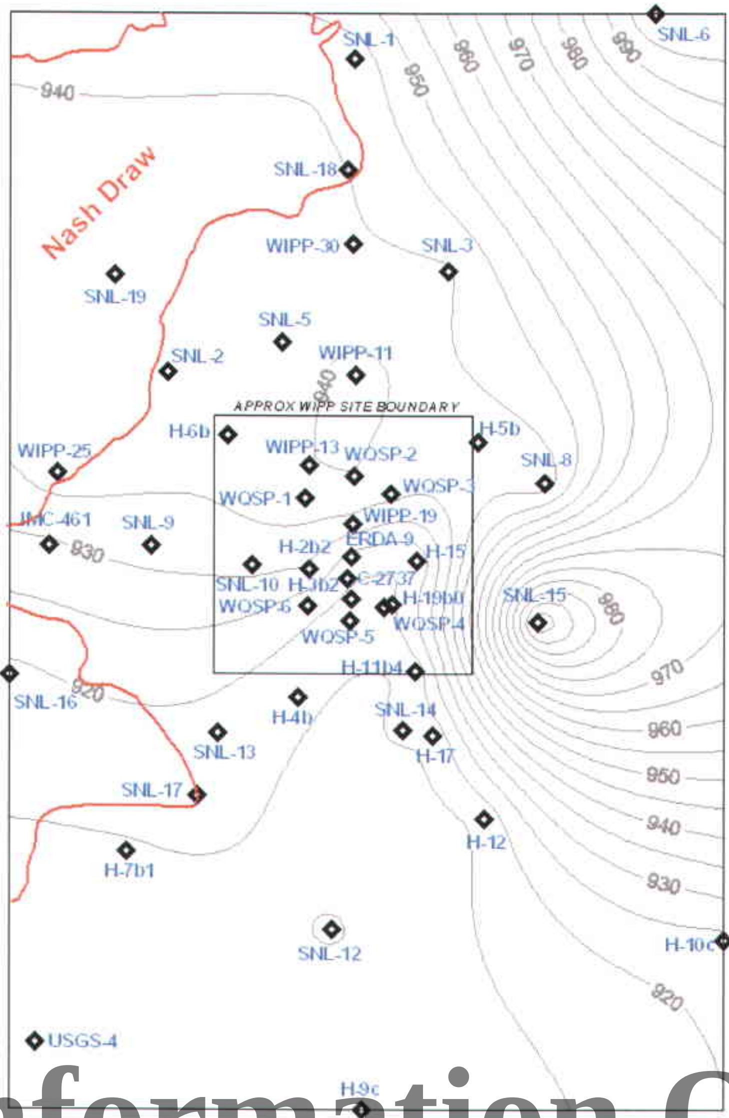
Precipitation and Infiltration

- WIPP receives ~330 mm of rainfall per year, most of which falls in major thunderstorms during the summer
- Outside of Nash Draw, infiltration is estimated to be 0.2-2 mm/yr
- Within Nash Draw, closed catchment basins drain to sinkholes and caves in Rustler gypsum karst above the Culebra

Culebra Potentiometric Surface

Freshwater Head (m amsl)

May 2007



- **Groundwater flow in the Culebra is generally north to south**
- **Heads at SNL-6 and SNL-15 are estimated**

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Recharge and Discharge Areas

- The water crossing the WIPP site in the Culebra is believed to have fallen as precipitation some km to the north—no water in the Culebra at the WIPP site fell as precipitation on the site
- The northeastern arm of Nash Draw *may* be the nearest recharge location for the Culebra at WIPP
- Recharge to the Culebra also occurs SW of the WIPP site, creating a groundwater divide
  - Most of the flow down Nash Draw passes to the west of the divide, moving toward Malaga Bend on the Pecos
  - The flow across the WIPP site passes to the east of the divide, moving toward the south and the Balmorhea-Loving trough

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Hydrological Investigations

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Hydrological Investigations

- Drilling/coring of 90 Culebra wells
- Hydraulic testing at 65 Culebra well pads
- Monitoring of water levels and/or fluid pressures beginning in 1977
- Modeling of water-level rise

Well Network

Wells

- 90 Culebra wells drilled and/or cored on 63 pads
- 60 wells purposely drilled to Culebra
- 12 wells recompleted to Culebra on multiwell pads
- 18 wells of opportunity—holes drilled for other purposes converted to Culebra wells
- 2 pre-WIPP wells tested and/or monitored
- 19 wells have been completed since the CCA

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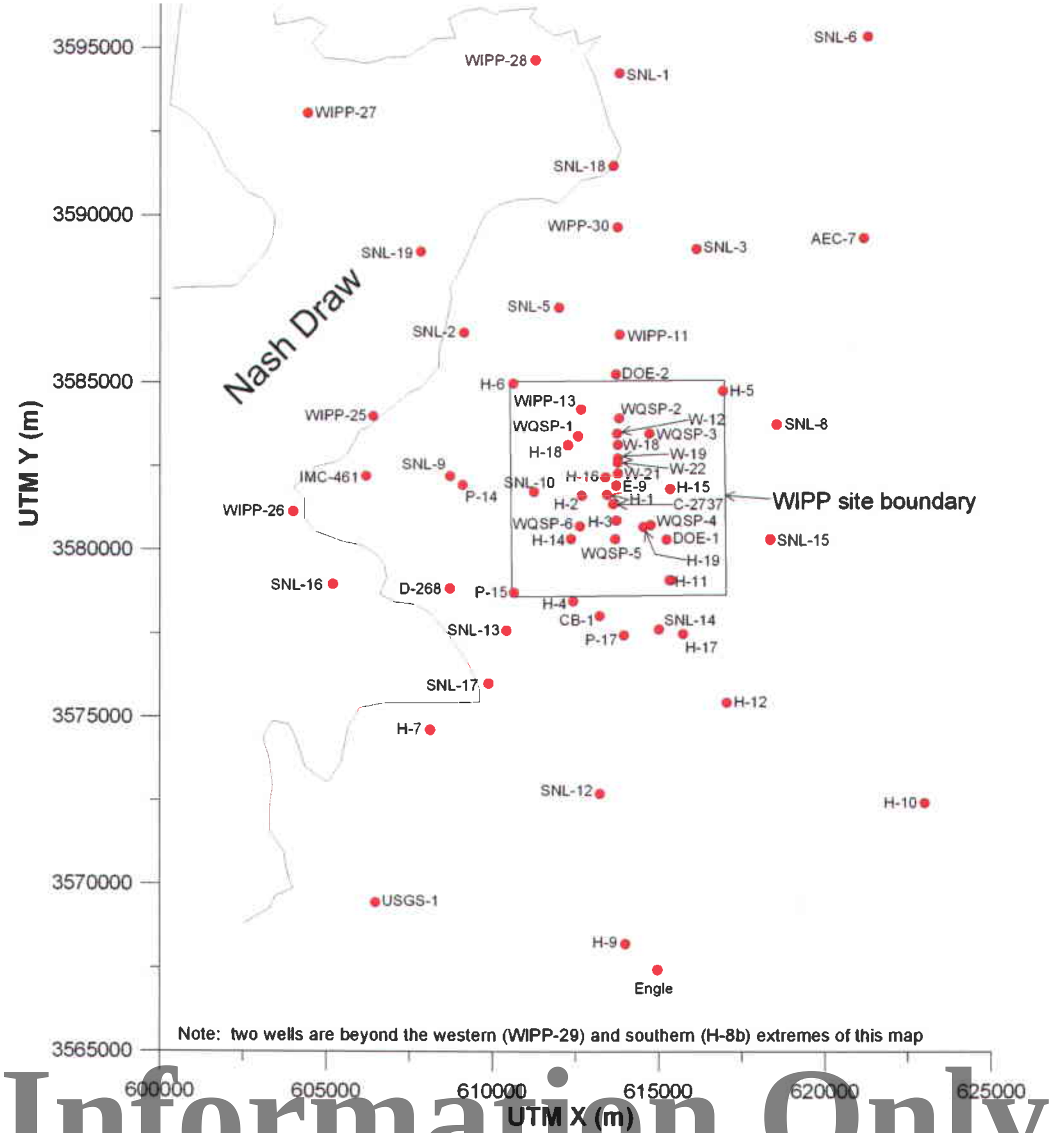
Past and Present Culebra Well Locations



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Reasons for Drilling Wells

- Spatial coverage
- Investigate geologic anomalies or features of interest
- Investigate halite margins
- Investigate causes of water-level rise
- Confirm conceptual model
- Confirm high-T zone indicated by modeling
- Optimization of monitoring network
- Evaluate transport properties along off-site transport pathway

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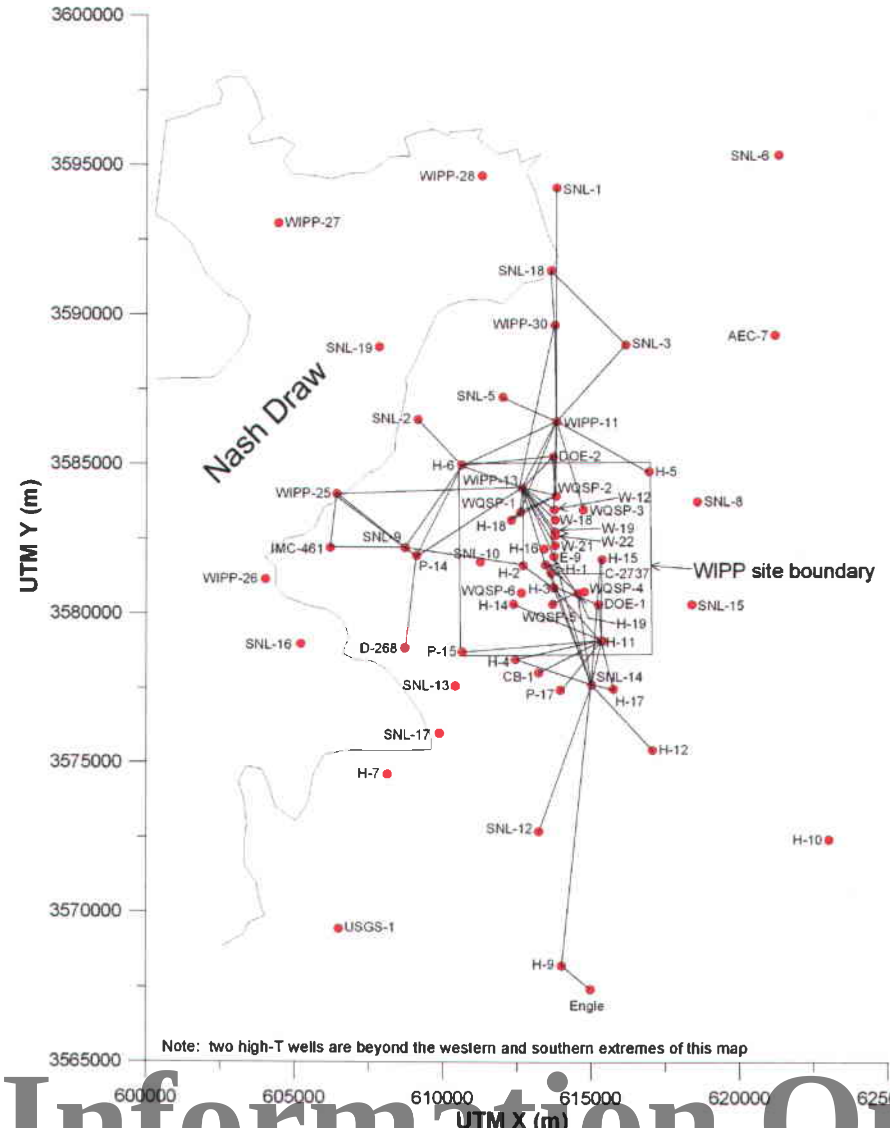
Hydraulic Testing

Hydraulic Testing

- 48 single-well tests
  - 26 slug tests
  - 22 pumping tests
- 7 pumping tests with observation wells on pad (r < 43 m)
- 6 short-term (<4 days) pumping tests with responses observed at wells 300-3500 m away
- 7 long-term (19-121 days) pumping tests with responses observed at wells up to 9.5 km away

Pumping and Responding Wells



Hydraulic-Testing Observations

- Many hydraulic test responses do not match homogeneous, single-porosity, radial-flow type curves
- Wells that can sustain pumping rates greater than 0.1 L/s (~1.6 gpm) typically had fractured Culebra core and show double-porosity hydraulic responses
- Weak pad-scale anisotropy
- Large-scale asymmetrical directional dependence of responses
- Some large-scale responses seem inconsistent with single-well behavior (H-15, WIPP-30)
- Subradial flow dimensions
- Most well responses show no evidence of vertical leakage

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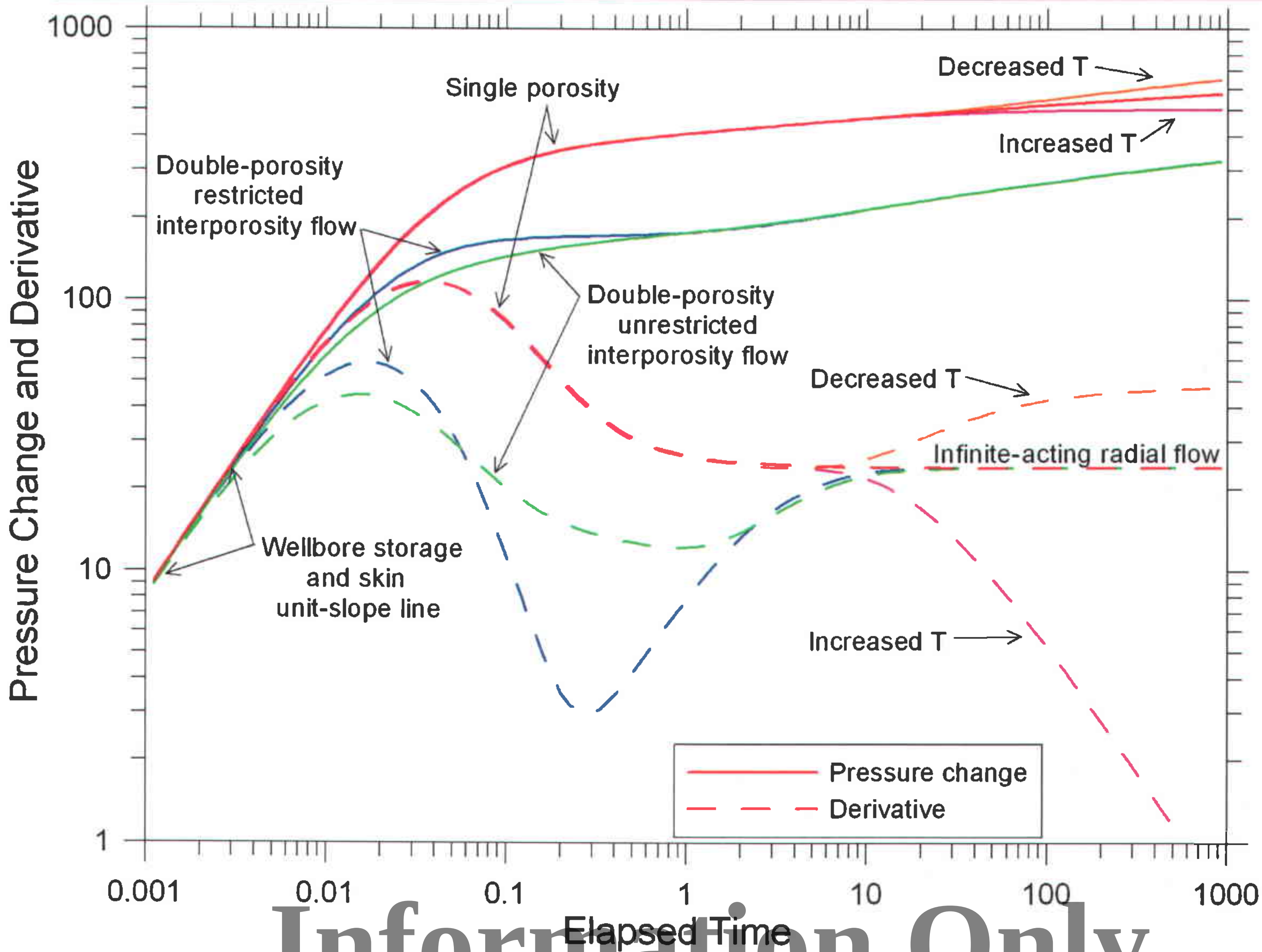
Diagnostic Plots



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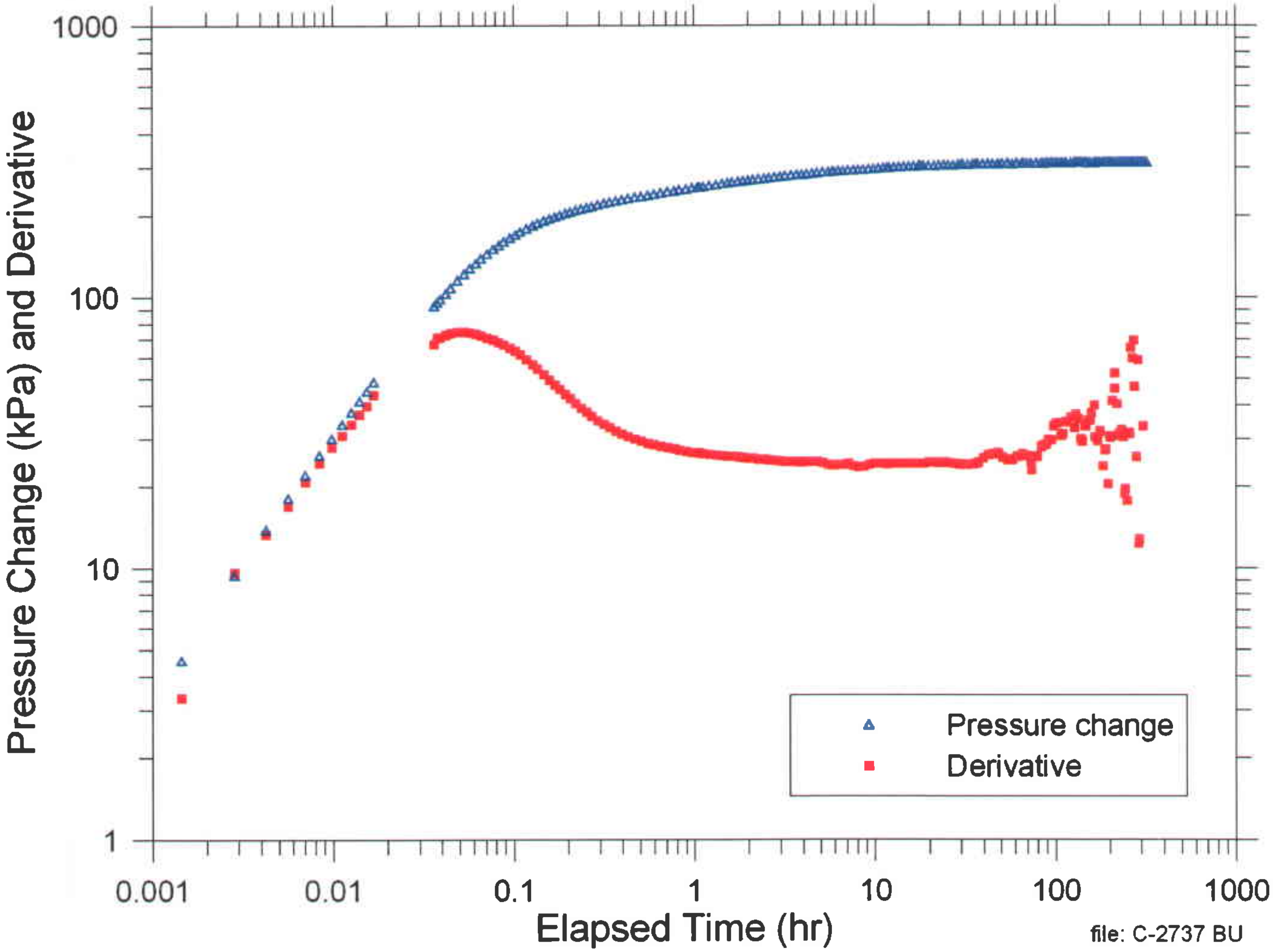
Well Responses Observed (1)



Single-porosity radial flow

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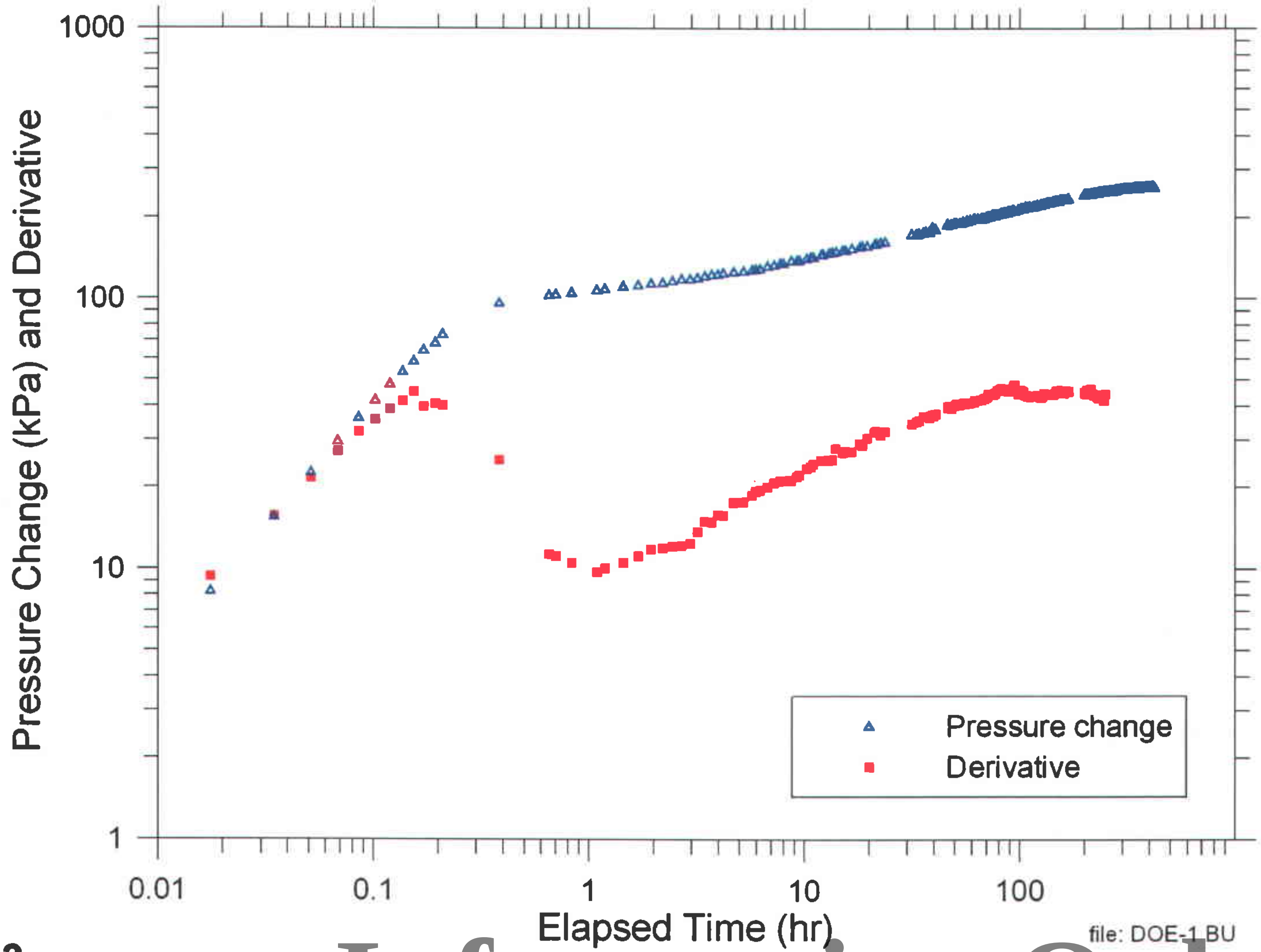
Well Responses Observed (2)



Double-porosity radial flow

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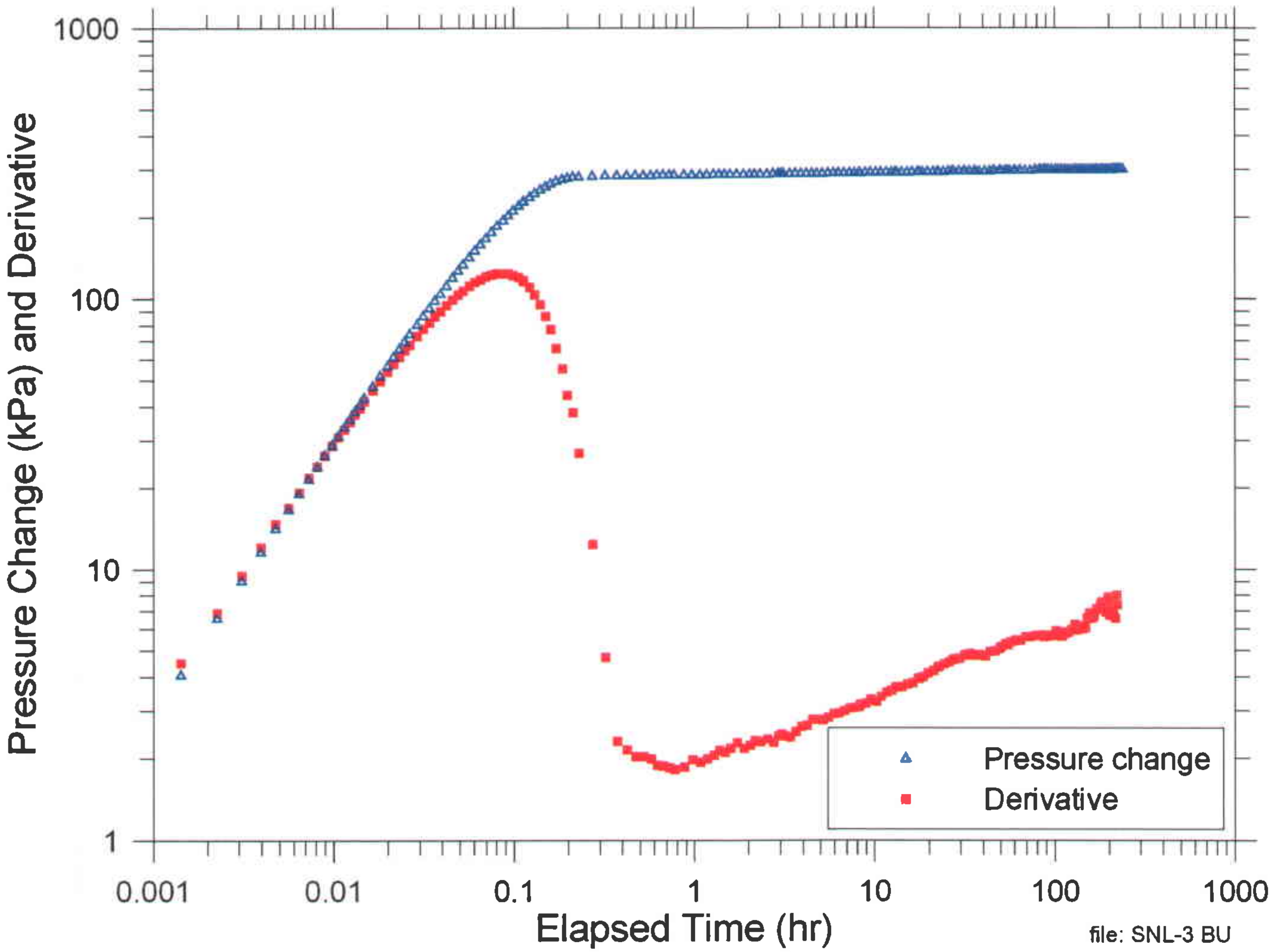
Well Responses Observed (3)



Increasing derivative indicative of decreasing T

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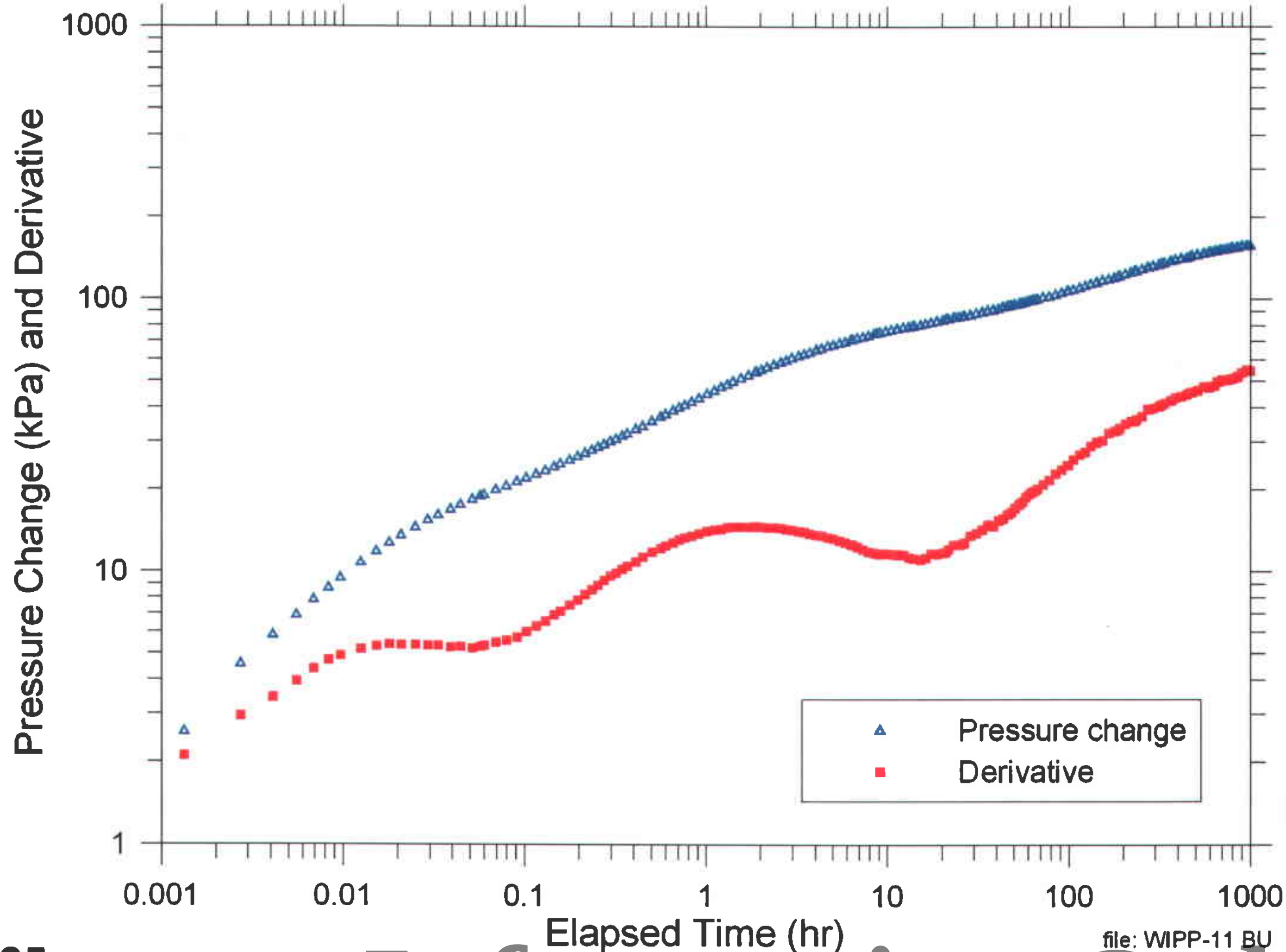
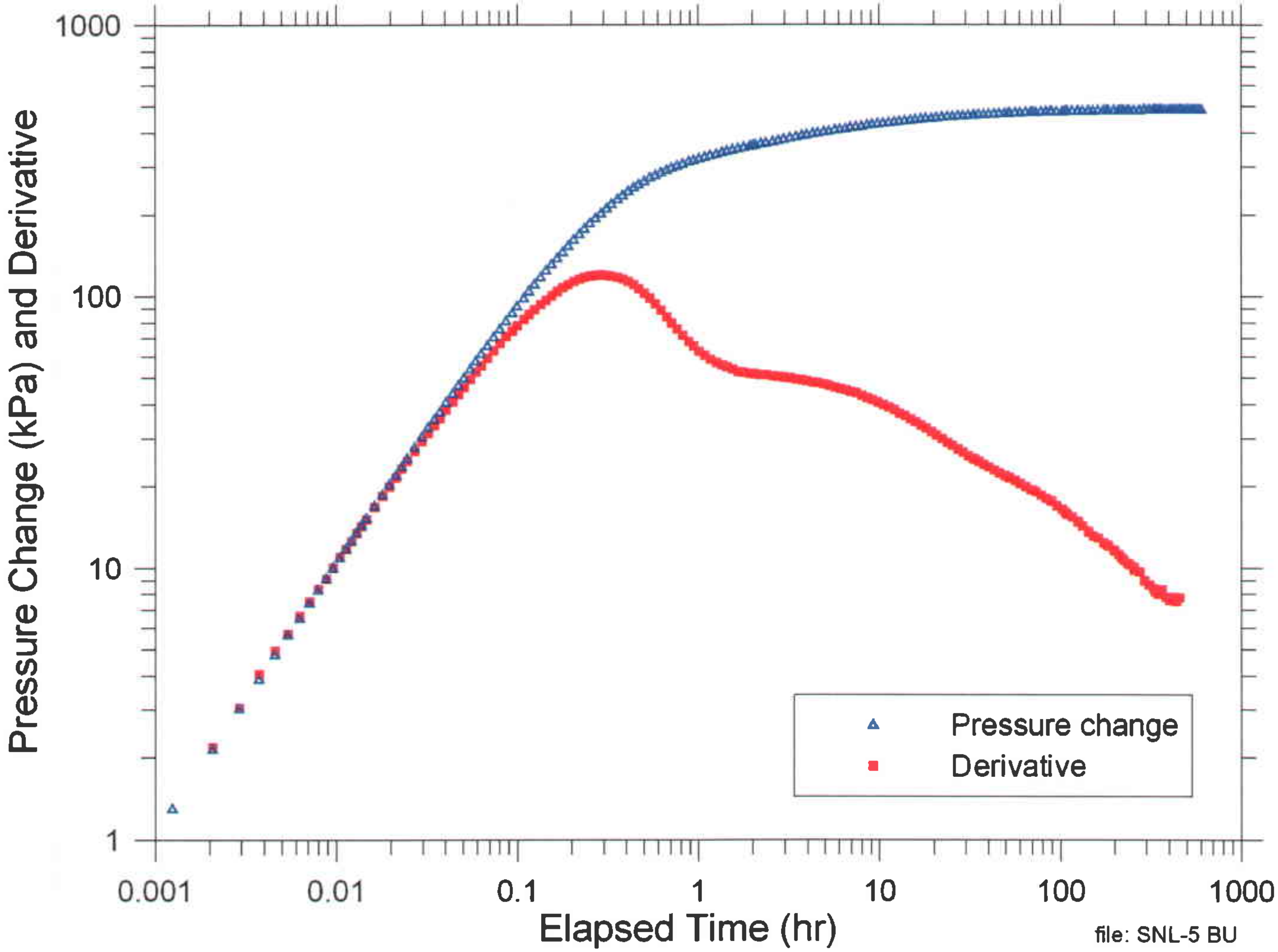
Well Responses Observed (4)



Oscillating derivative indicative of multiple zones of lower T

Well Responses Observed (5)



Decreasing derivative indicative of increasing T

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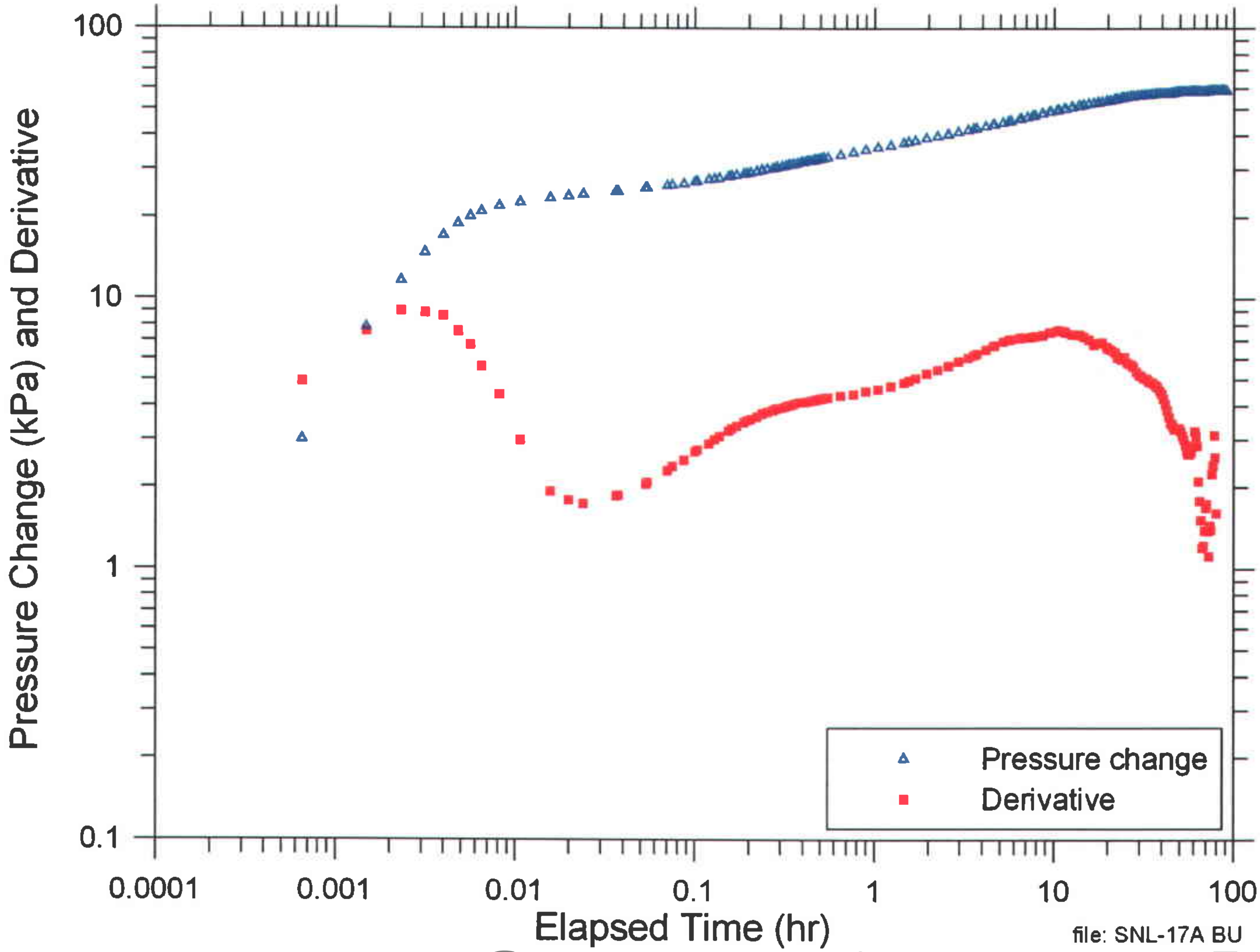
Well Responses Observed (6)



Changing derivative indicative of double-porosity, decreasing T, and increasing T

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Double Porosity

- Double-porosity hydraulic behavior is observed in a fractured medium when most of the permeability is provided by the fractures while most of the storage is provided by the matrix
- As fracture density increases, the matrix can release fluid to the fractures more quickly and the double-porosity response fades
- Double-porosity behavior is typically seen in the Culebra when $T \geq 6E\text{-}6\ m^2/s$

Hydraulic-Testing Analysis

Two codes used for most hydraulic-test analysis:

- Interpret2000
- nSIGHTS

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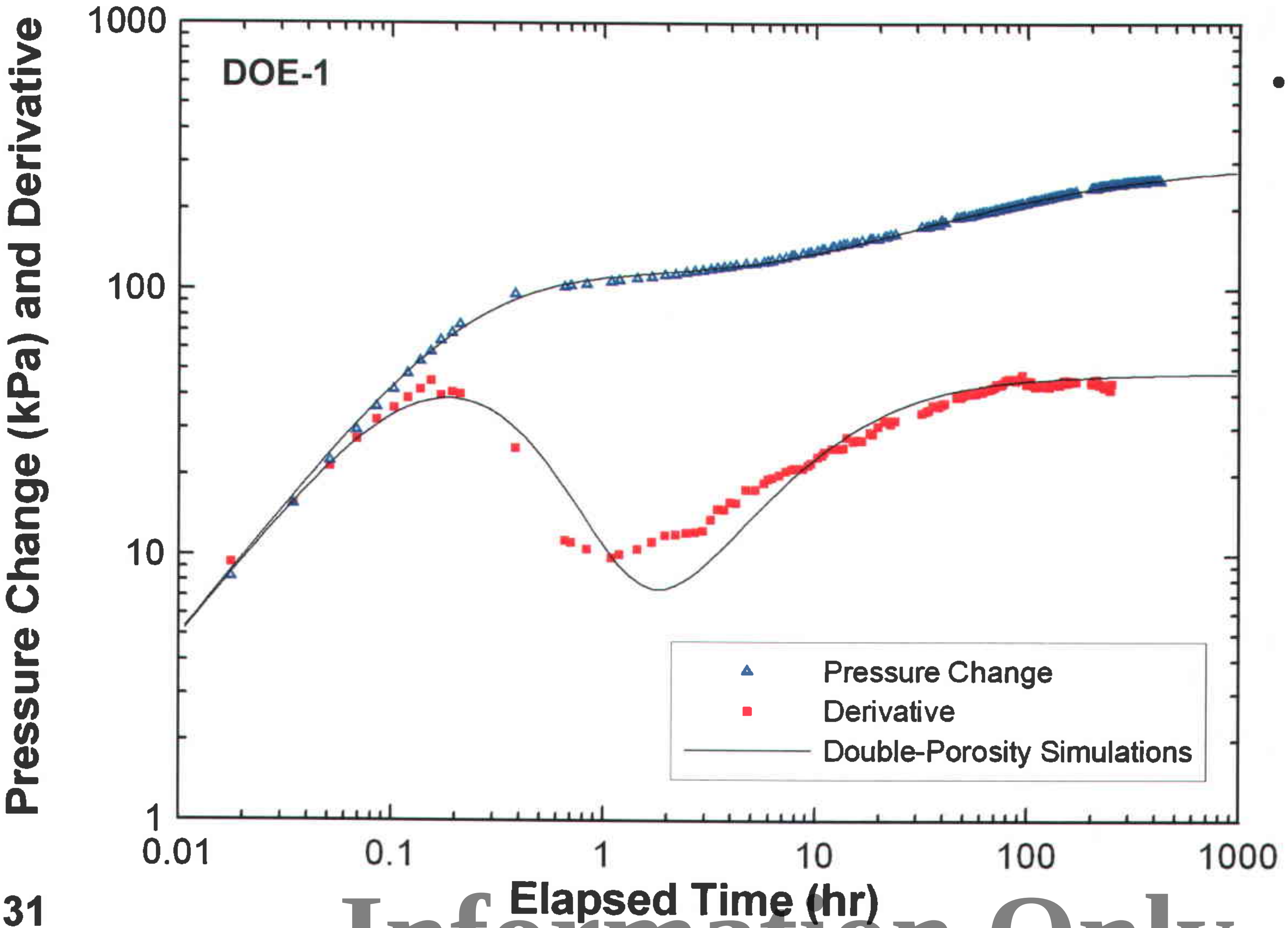
Interpret2000

- Petroleum industry code developed by A.C. Gringarten and Scientific Software-Intercomp
- Provides automated fitting to analytical solutions for radial systems
- Can only fit to data from a single flow period presented in a single way
  - Log-log pressure change
  - Log-log derivative
  - Horner plot
  - Cartesian plot
- Includes wellbore storage, skin, single- or double-porosity, external boundaries

Intepret2000 Simulation of Pumping Well Response



- Double-porosity model with wellbore storage and skin

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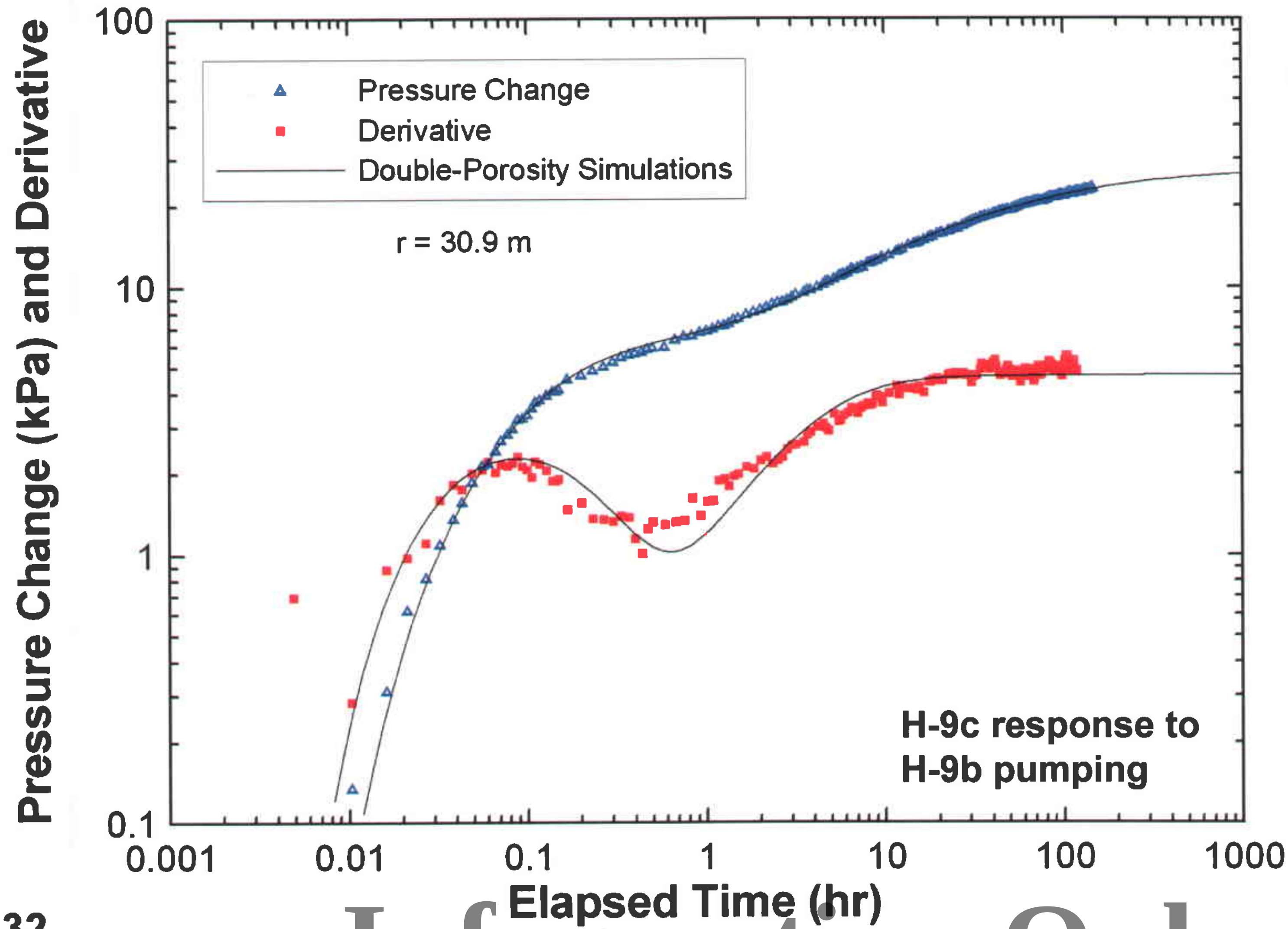
Interpret 2000 Simulation of Nearby Observation Well Response



- Line-source double-porosity model

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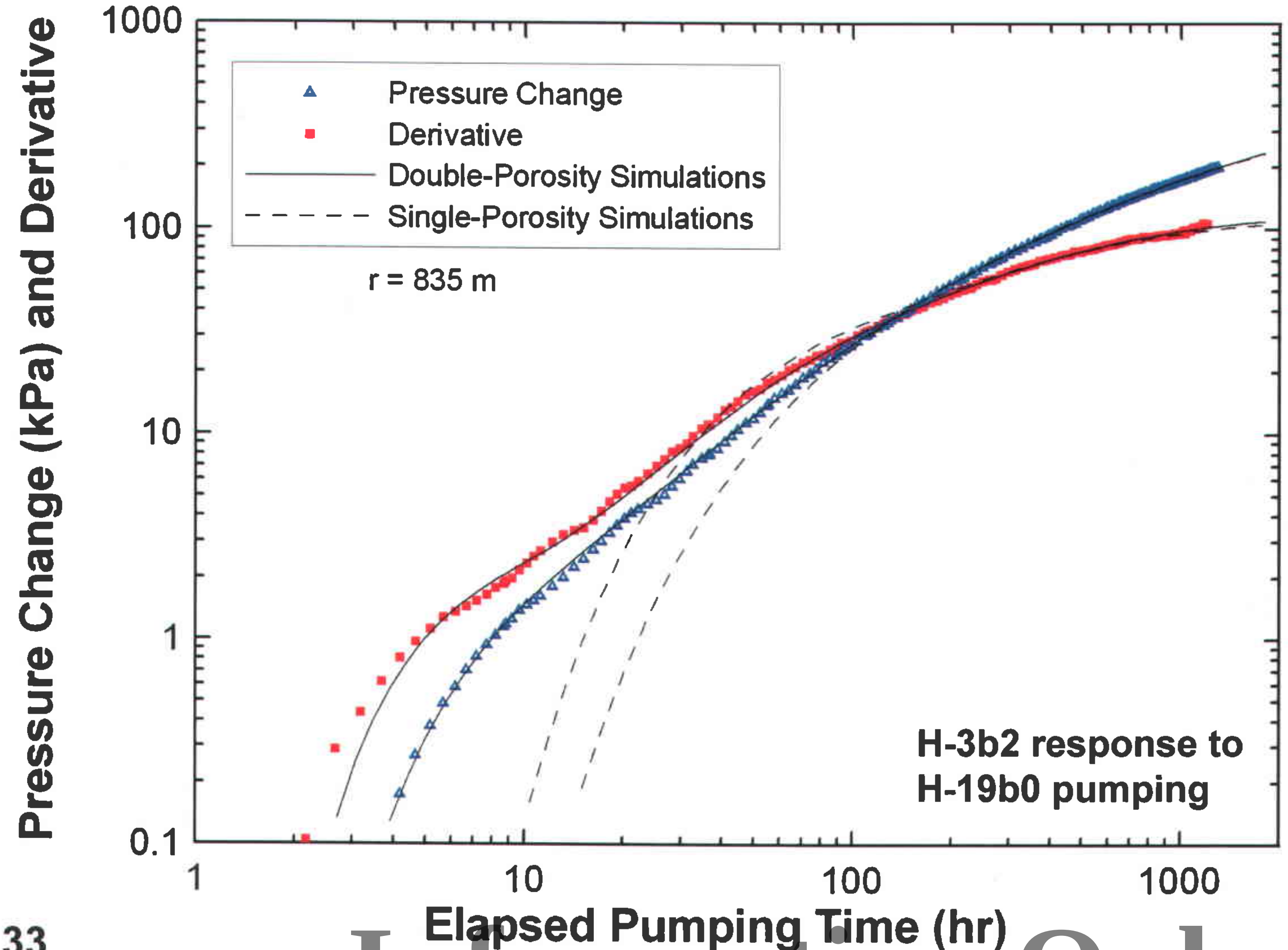
Interpret 2000 Simulation of Distant Observation Well Response



- Comparison of line-source double-porosity and single-porosity models

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nSIGHTS

- n-dimensional Statistical Inverse Graphical Hydraulic Test Simulator
- Modular, object-oriented code written in C++ under Windows
- Simulates single-phase flow to/from a well using graph-theory implementation of finite differences
- Treats heterogeneities as though they are symmetrically distributed around the well

nSIGHTS (2)

- Can simulate flow through a system having any flow dimension, as well as continually varying flow dimensions
- Includes graphical tools for statistical evaluation of parameter uncertainty
- Includes pressure and/or flow history preceding a test explicitly
- Performs simultaneous optimization to multiple constraints
- Developed under Sandia sponsorship

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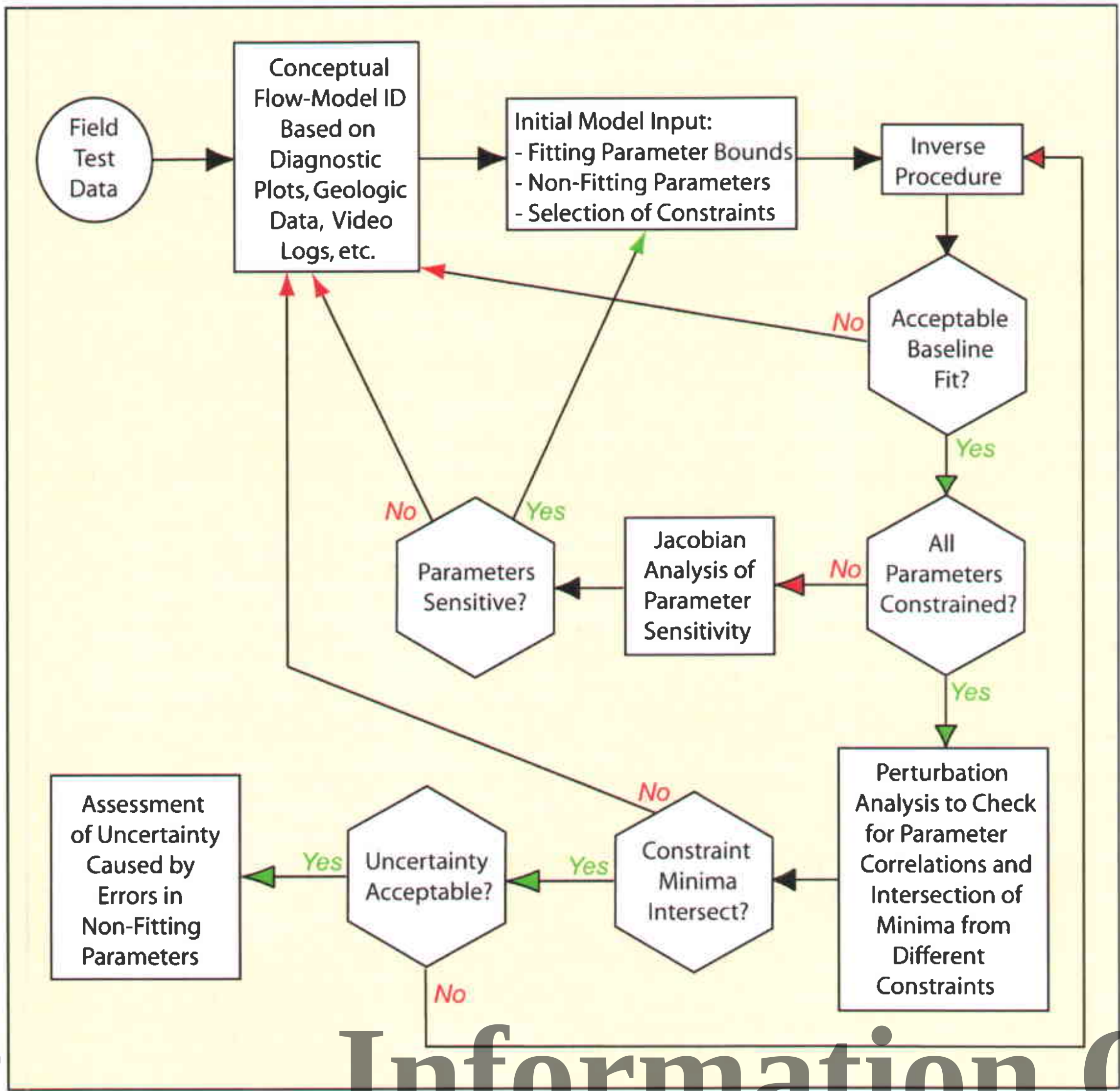
Flowchart of Analysis Process



- Initial analysis provides a "baseline" fit
- Perturbation analysis maps parameter space to find global minimum
- Uncertainty is quantified

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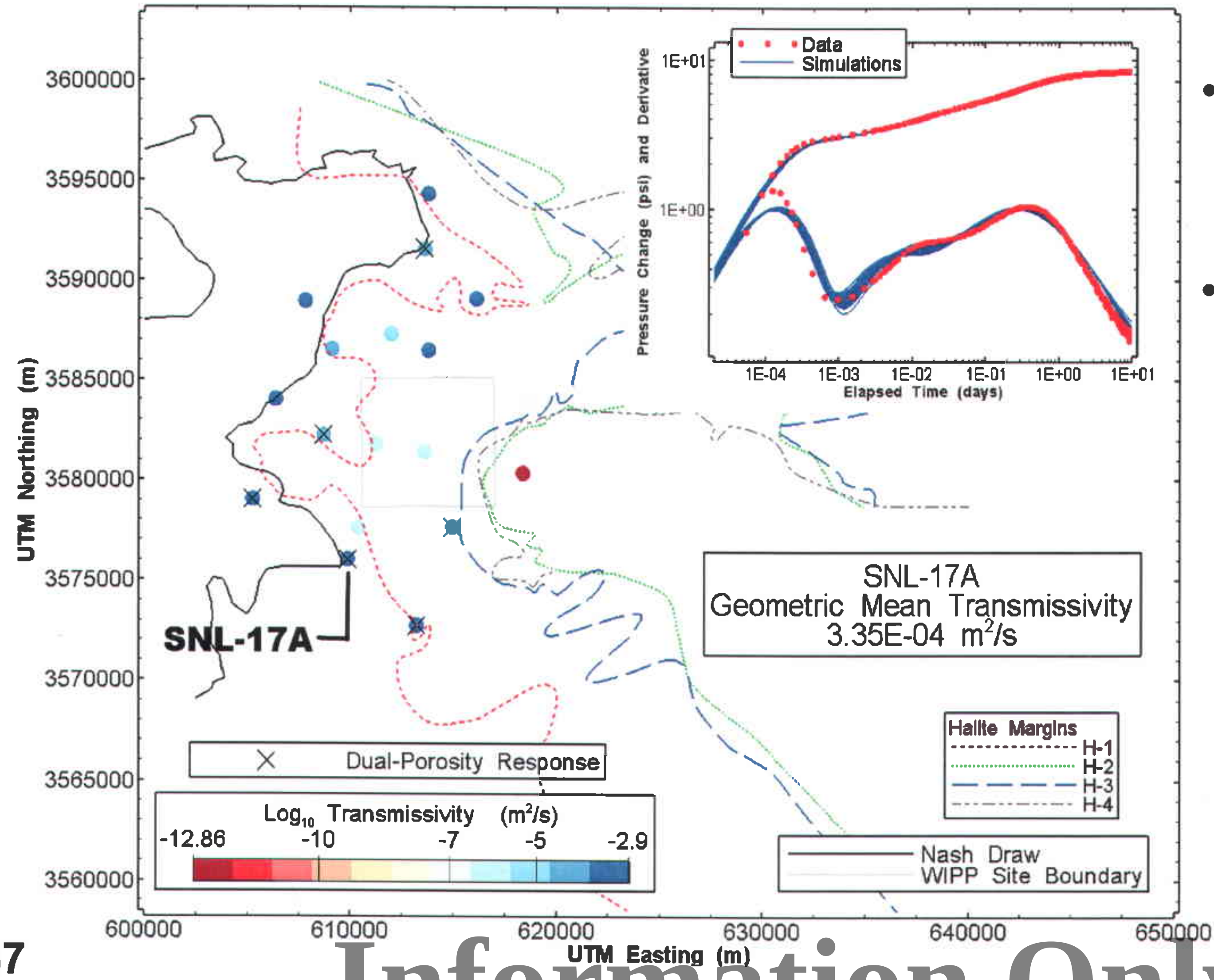
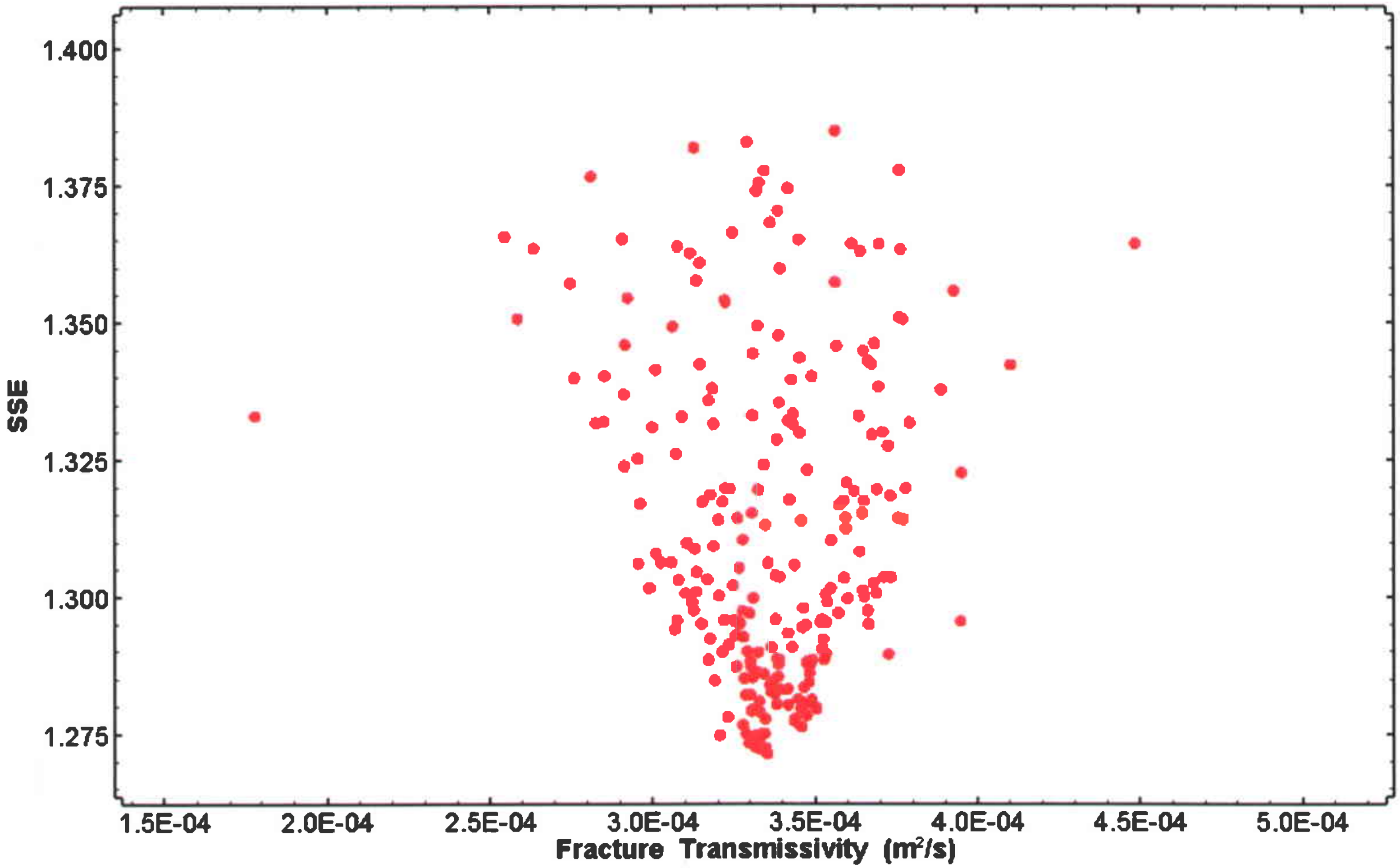
nSIGHTS Simulation (1)



- Double-porosity, radial-composite model
- Horsetail shows 246 simulations

nSIGHTS Simulation (1a)

SNL-17A: 246 perturbation T results



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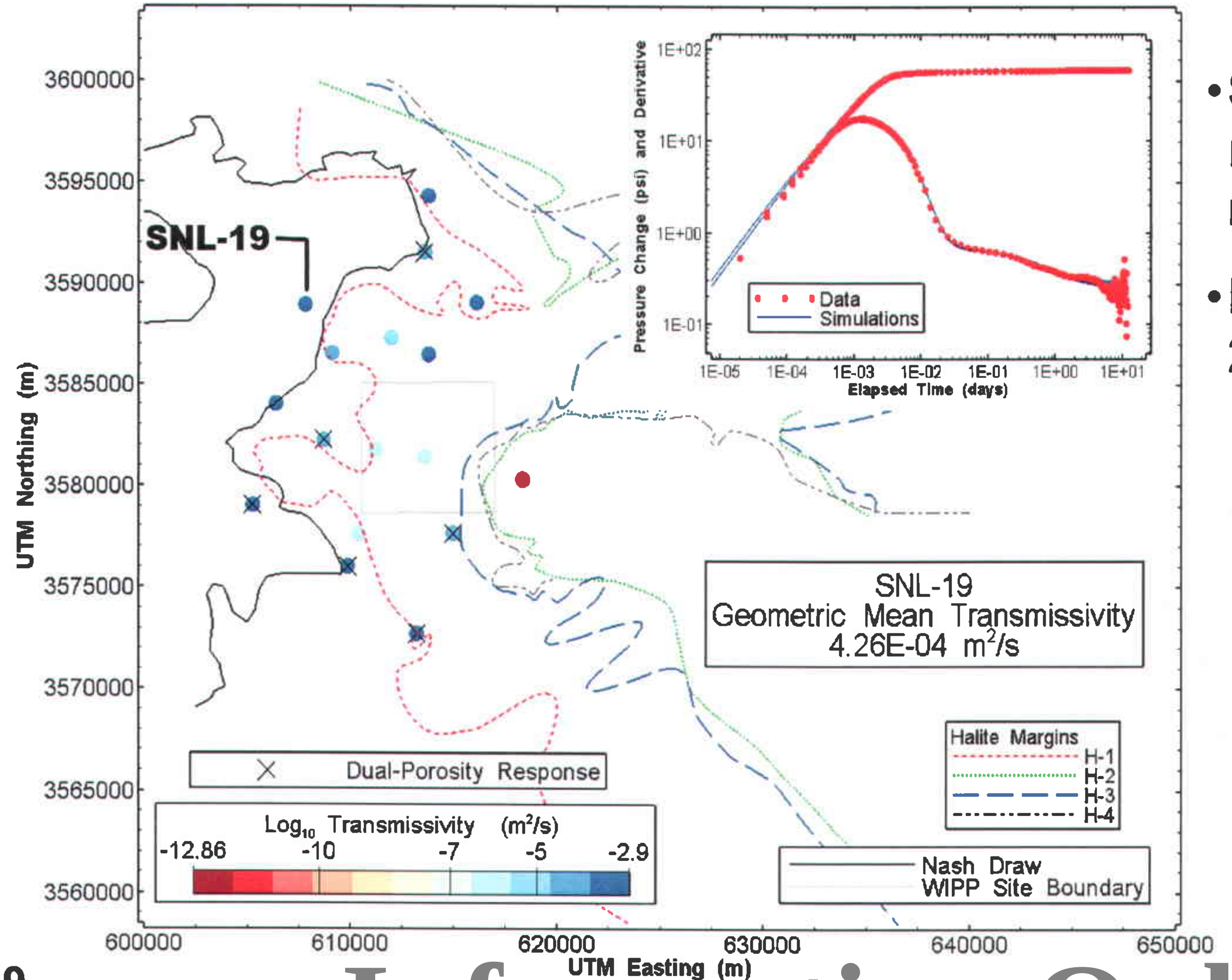
nSIGHTS Simulation (2)



- Single-porosity, radial-composite model
- Horsetail shows 239 simulations

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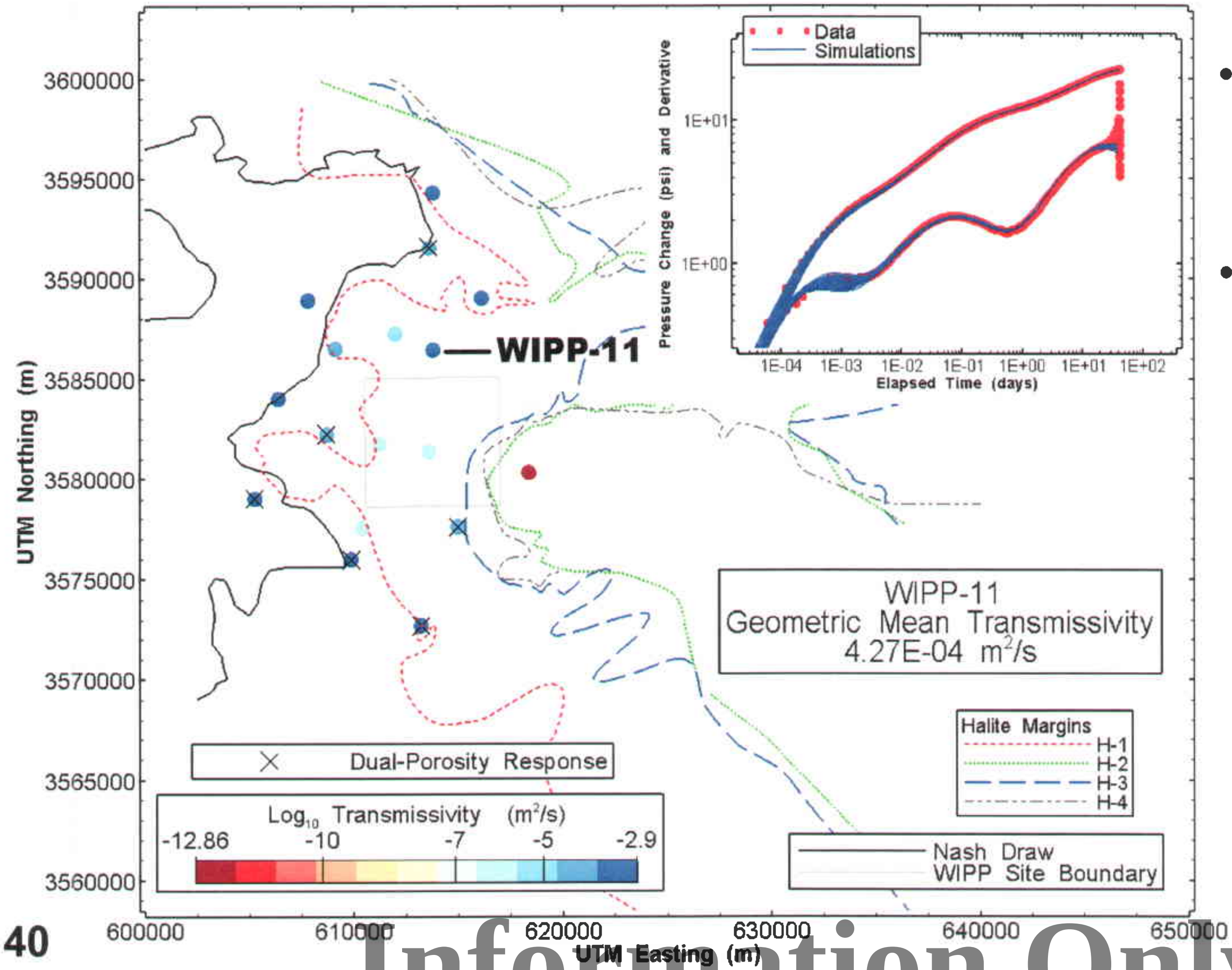
nSIGHTS Simulation (3)



- Single-porosity, radial-composite model
- Horsetail shows 40 simulations

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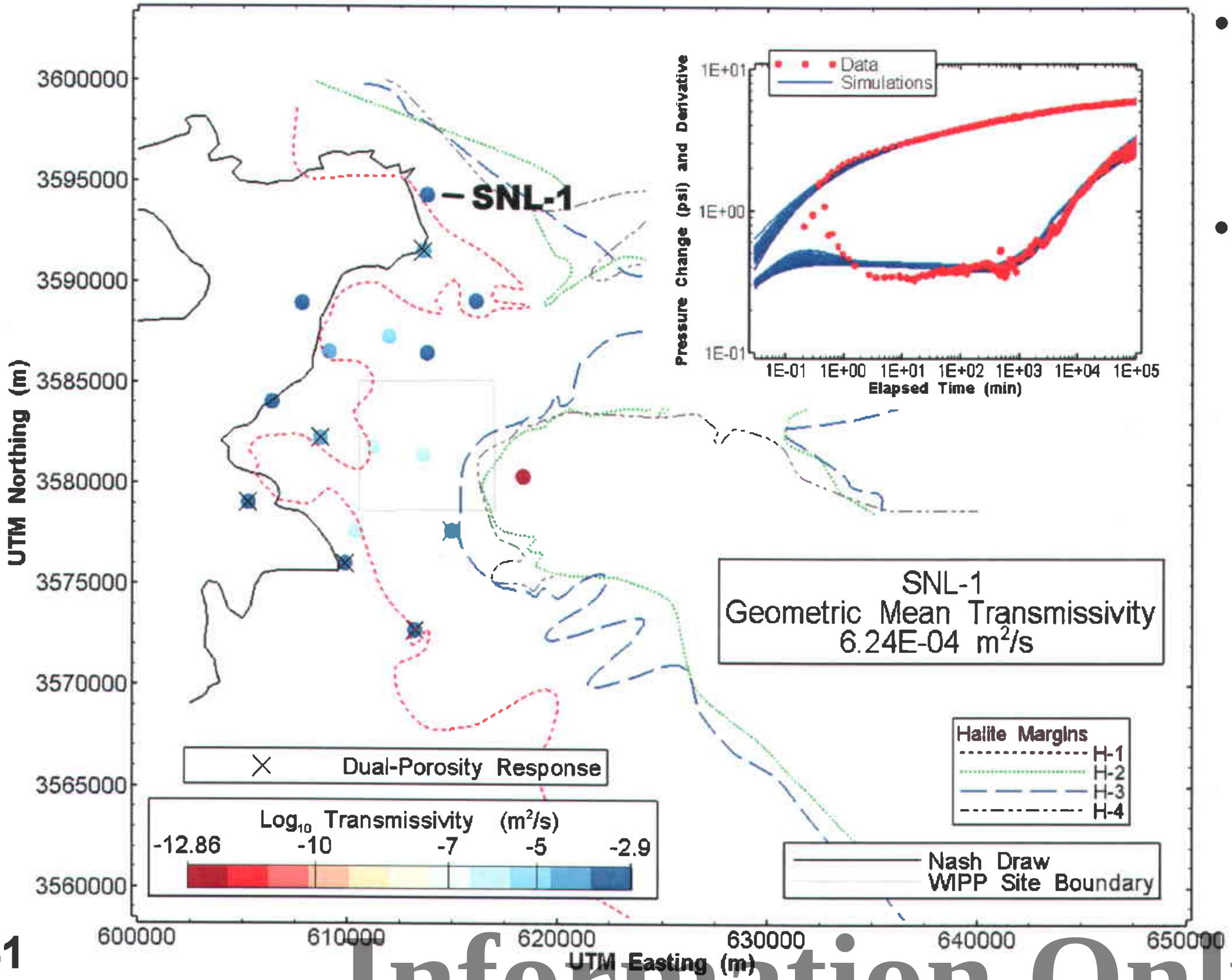
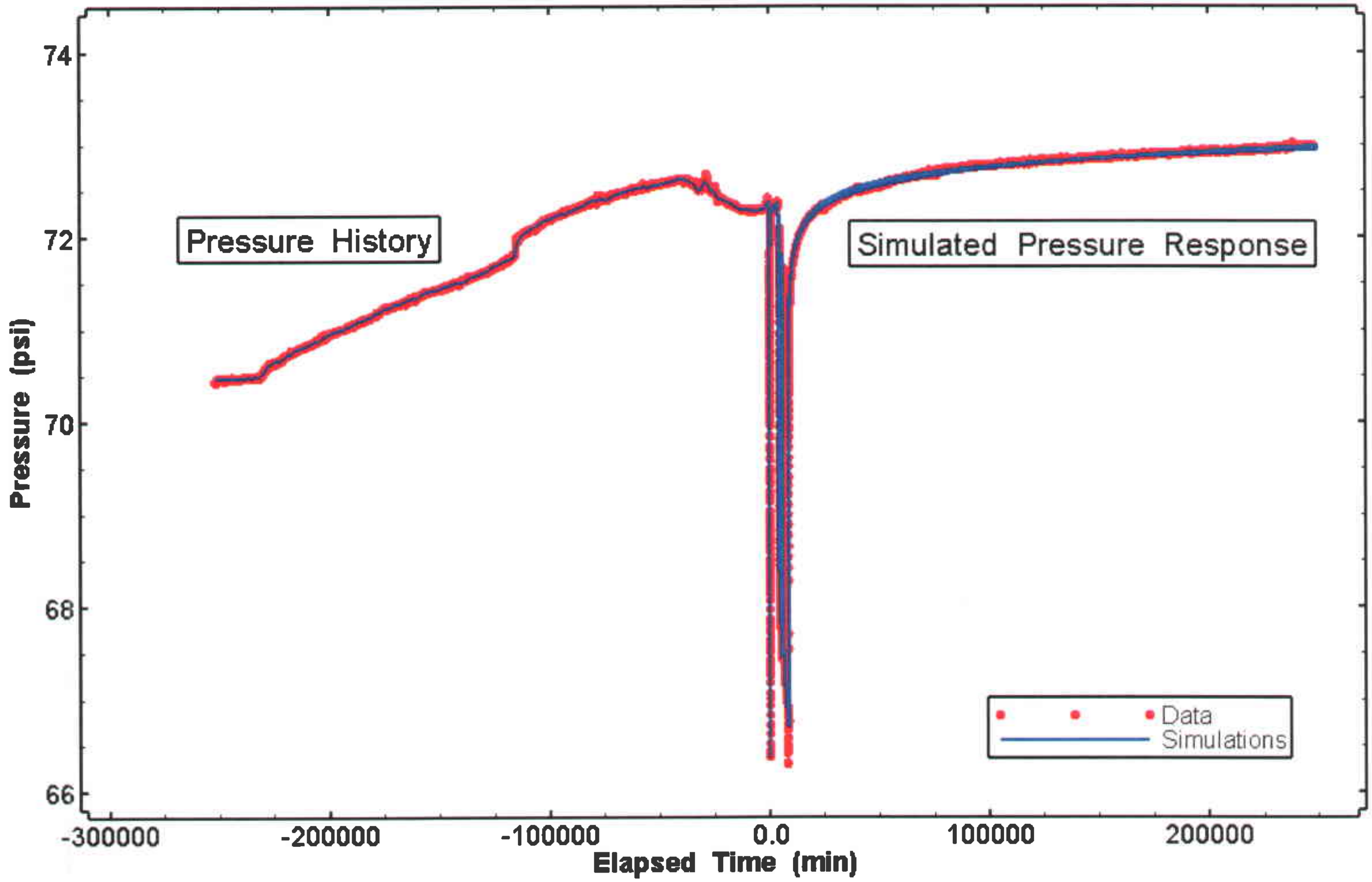
nSIGHTS Simulation (4)



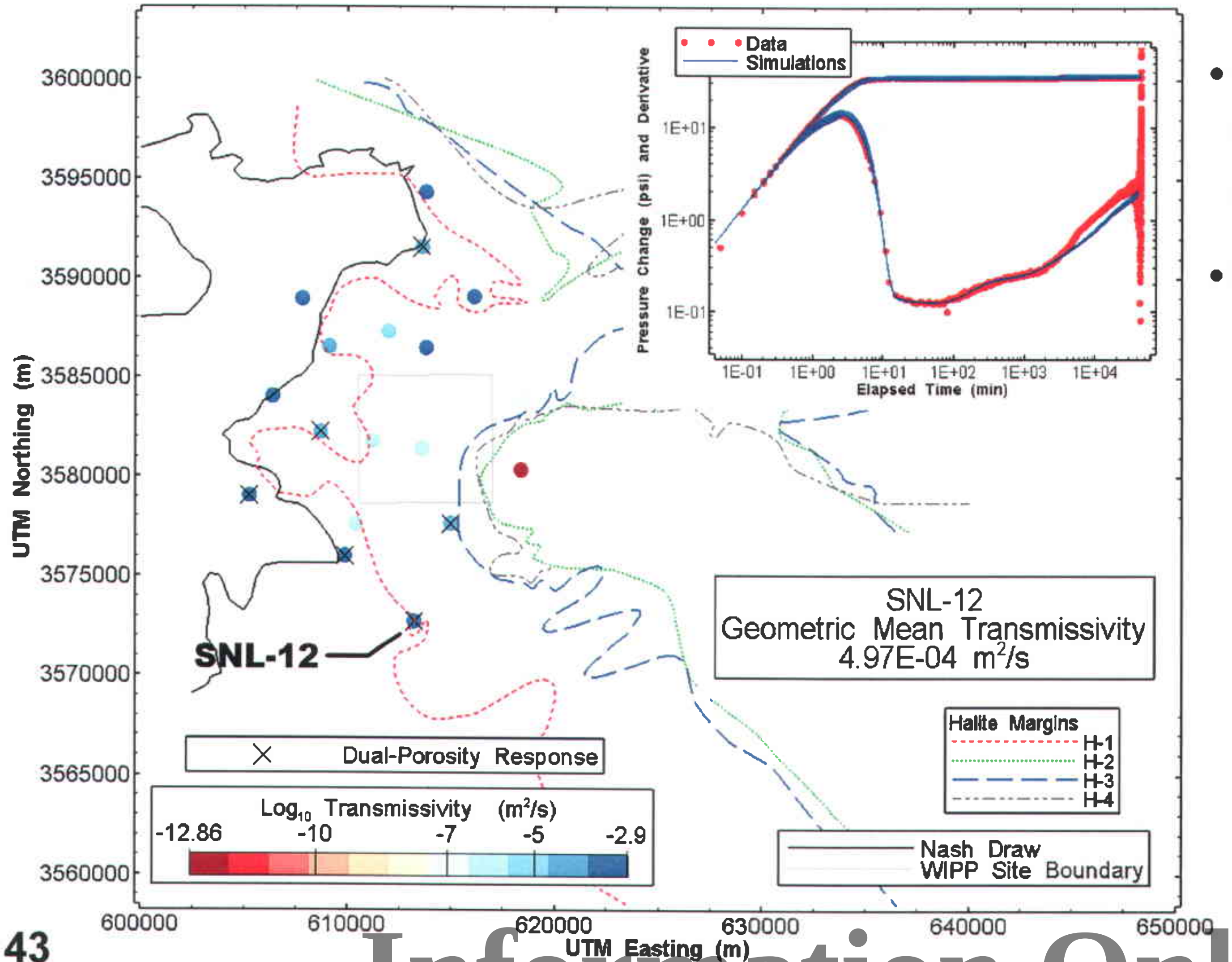
- Single-porosity, radial-composite model
- Horsetail shows 104 simulations

nSIGHTS Simulation (4a)



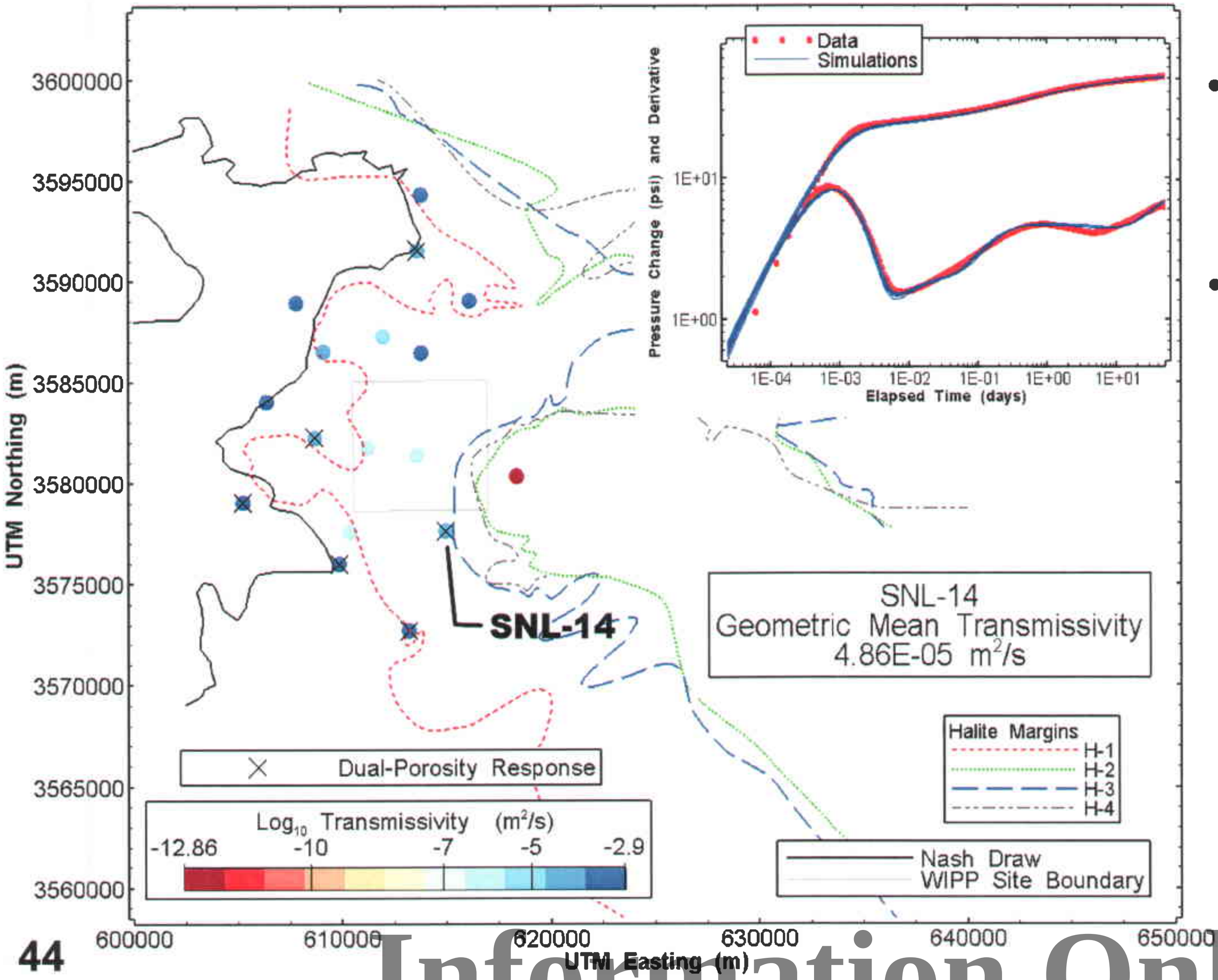
- SNL-1 pre-test pressure history included in simulations

nSIGHTS Simulation (5)



- Double-porosity, radial-composite model
- Horsetail shows 192 simulations

nSIGHTS Simulation (6)



- Double-porosity model with no-flow boundary
- Horsetail shows 46 simulations

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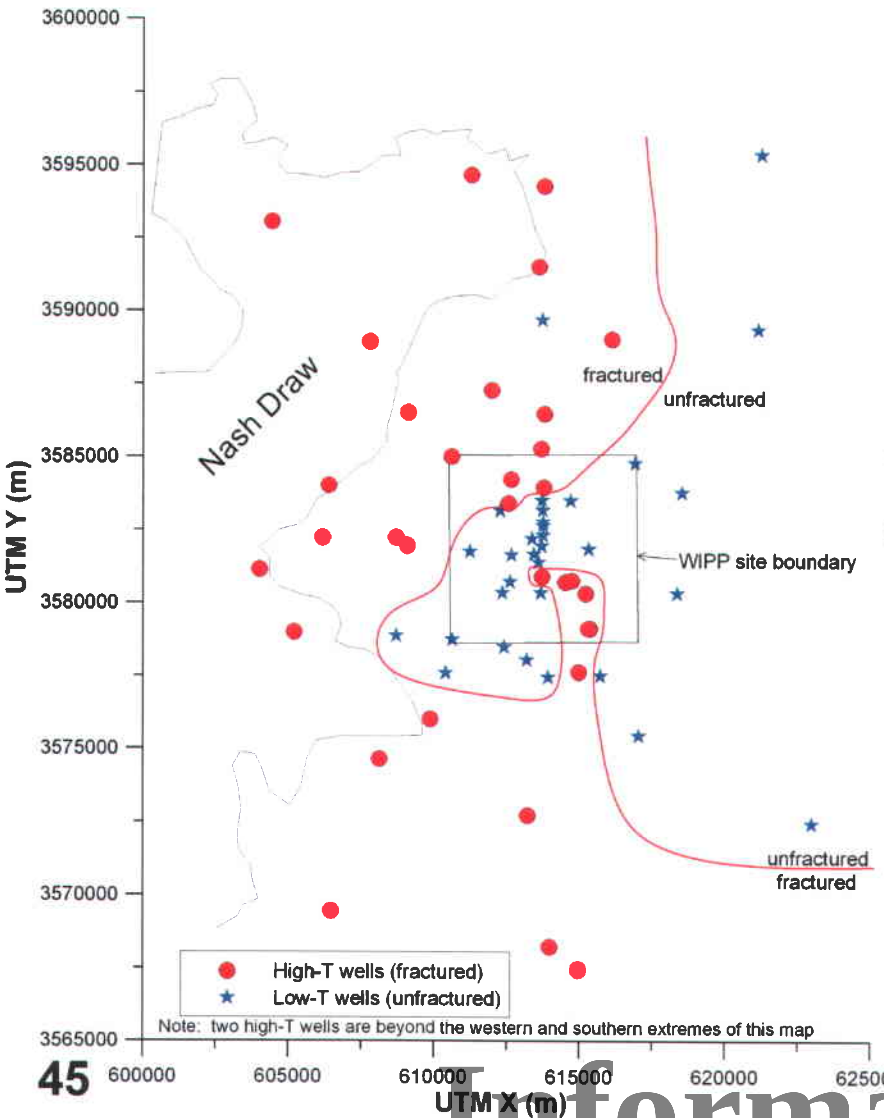
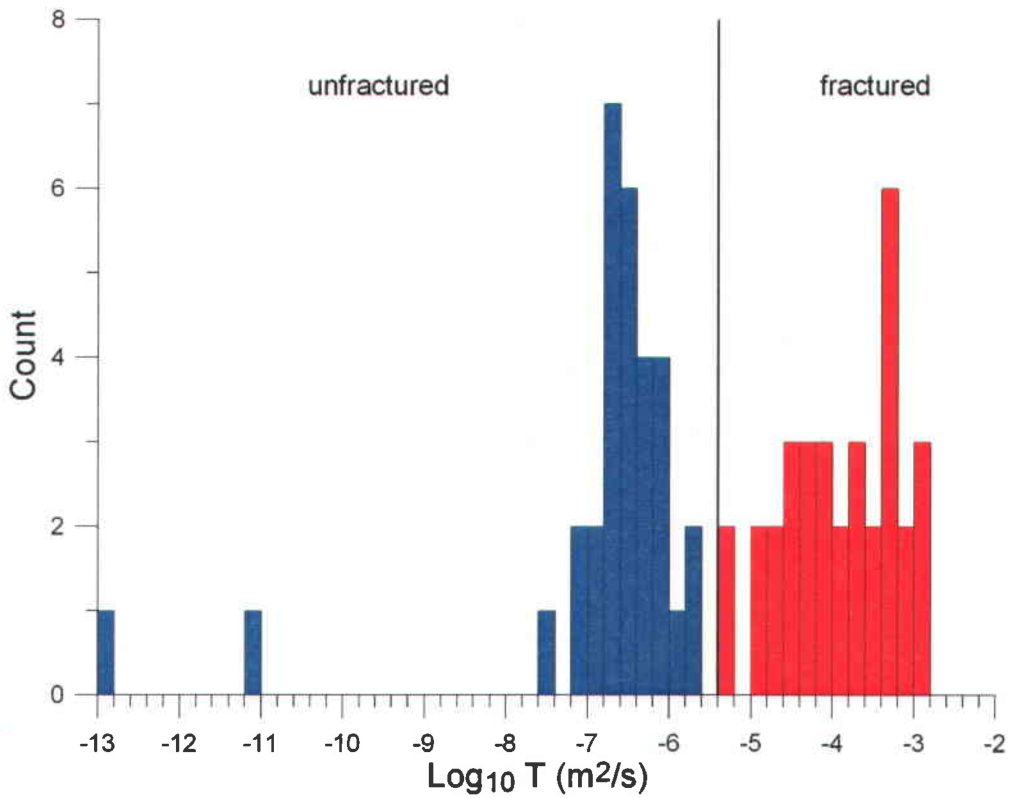
Culebra T Distribution





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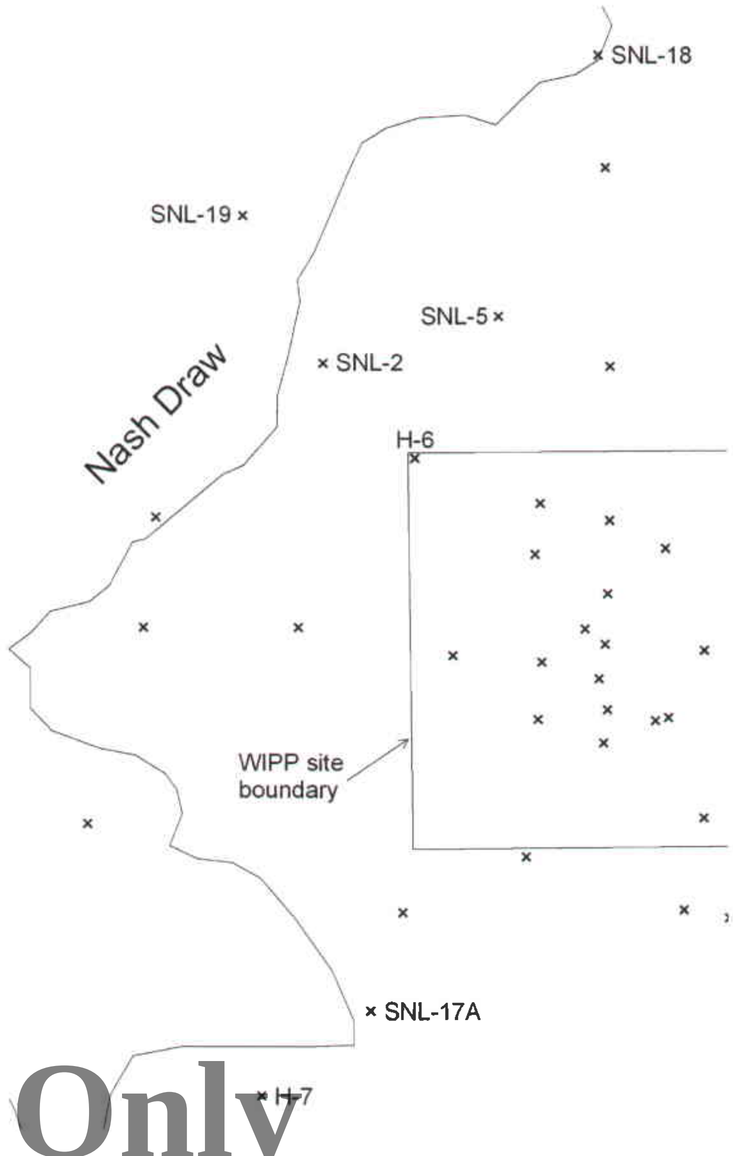
Leakage/Confinement

- Vertical leakage (representing incomplete confinement of the Culebra) manifests as a decline in the derivative at late time
- Increased transmissivity has the same signature
- The only well locations where such a decline was observed are:
  - SNL-2
  - SNL-5
  - SNL-17A
  - SNL-18
  - SNL-19
  - H-6
- H-7 is the only multiwell pad where the inferred S value might reflect unconfined conditions (1E-2)



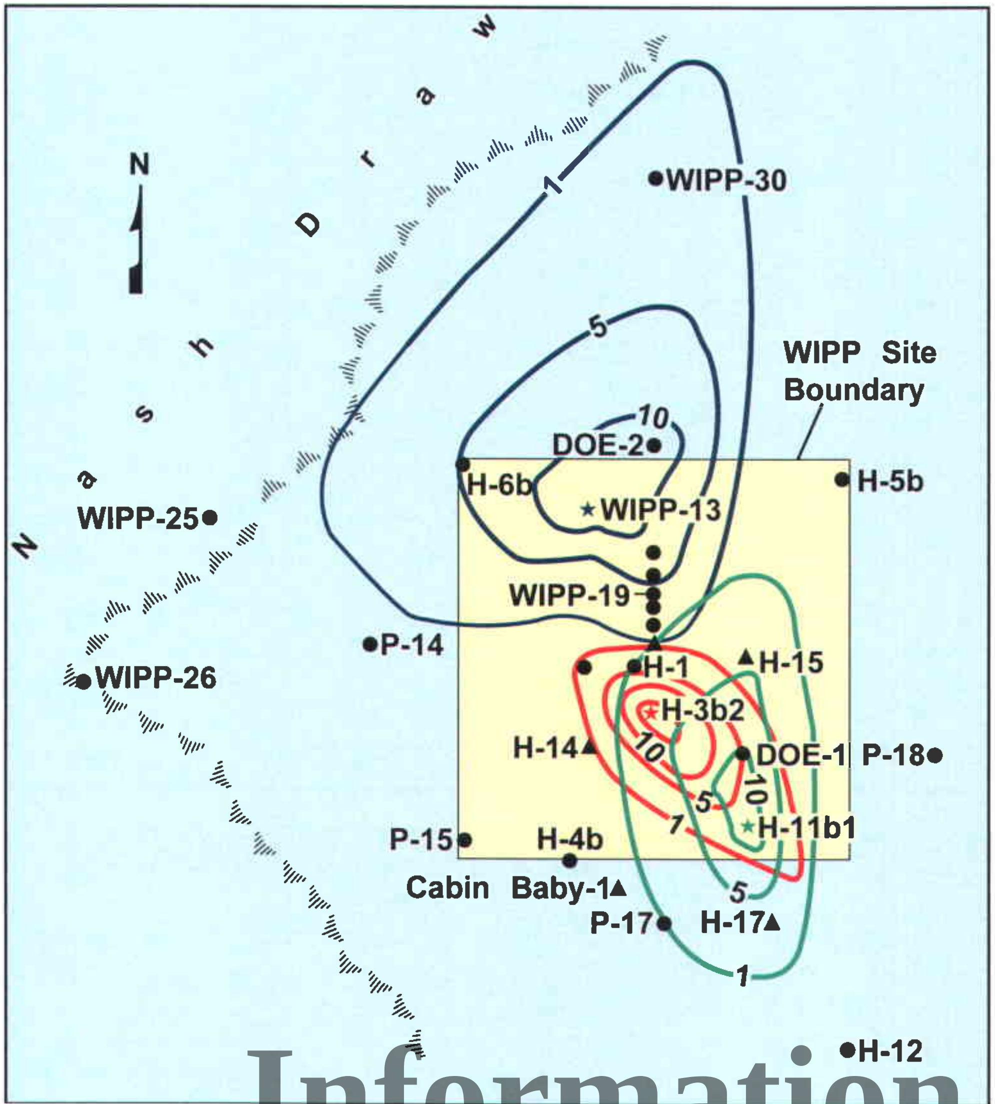
Pad-Scale Pumping Tests

- Observation wells show double-porosity when $T \geq 6E\text{-}6\ m^2/s$
- Relatively weak anisotropy
  - H-6: T_{max}/T_{min} = 1.6, N13°W
  - H-19: T_{max}/T_{min} = 1.2, N8°W
- Storativity ranges from 1E-5 to 1E-2

Large-Scale Pumping Tests

- Show strong directional dependence of responses
- Definite indication of heterogeneity
- Only hydraulic diffusivity (D), the ratio of transmissivity and storativity, can be inferred from an observation well response

Drawdown Responses to Large-Scale Pumping Tests



Pumped wells

H-3b2: 62 days @ 0.3 L/s

WIPP-13: 36 days @ 1.9 L/s

H-11b1: 63 days @ 0.4 L/s

Drawdown contours in meters

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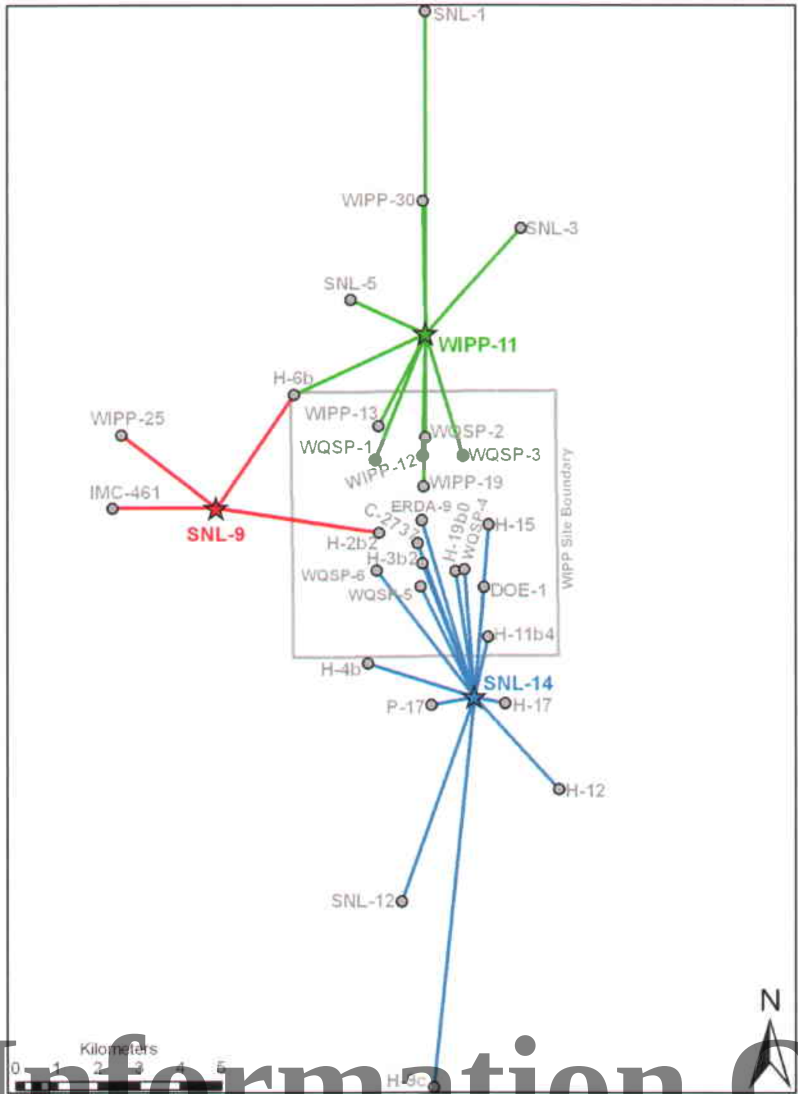
Recent Large-Scale Pumping Tests



Pumped wells

SNL-9: 22 days @ 2 L/s

WIPP-11: 19 days @ 2.2 L/s

SNL-14: 22 days @ 1.9 L/s

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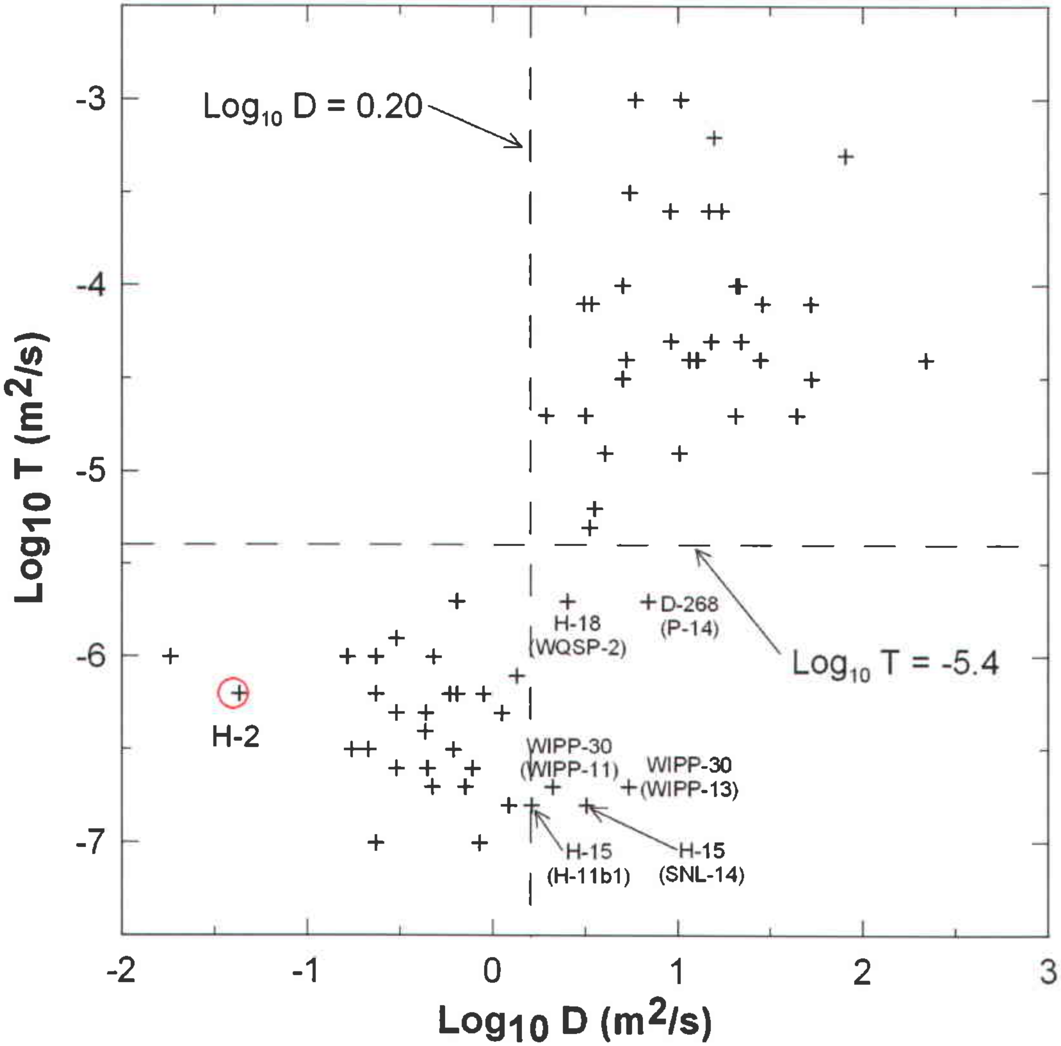
Diffusivity



- Plot $\log_{10}$ T values from single-well tests against $\log_{10}$ D values from multi-well tests
- All $\log_{10}$ D values > 0.29 are associated with high-T wells except D-268, H-15, H-18, and WIPP-30
- All other low-T wells have $\log_{10}$ D < 0.2
- $\log_{10}$ D values ≥ 0.2 reflect fracture connections

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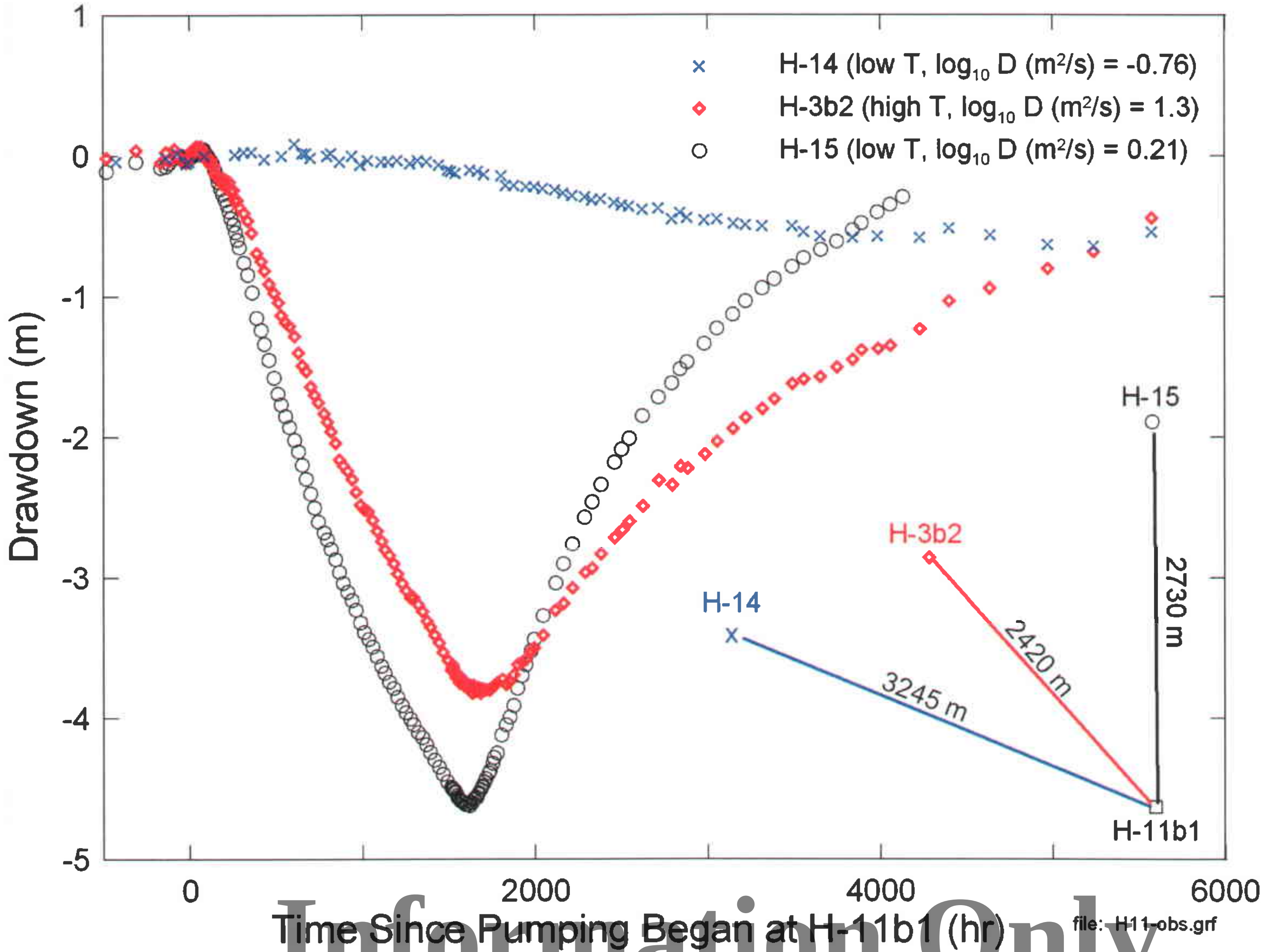
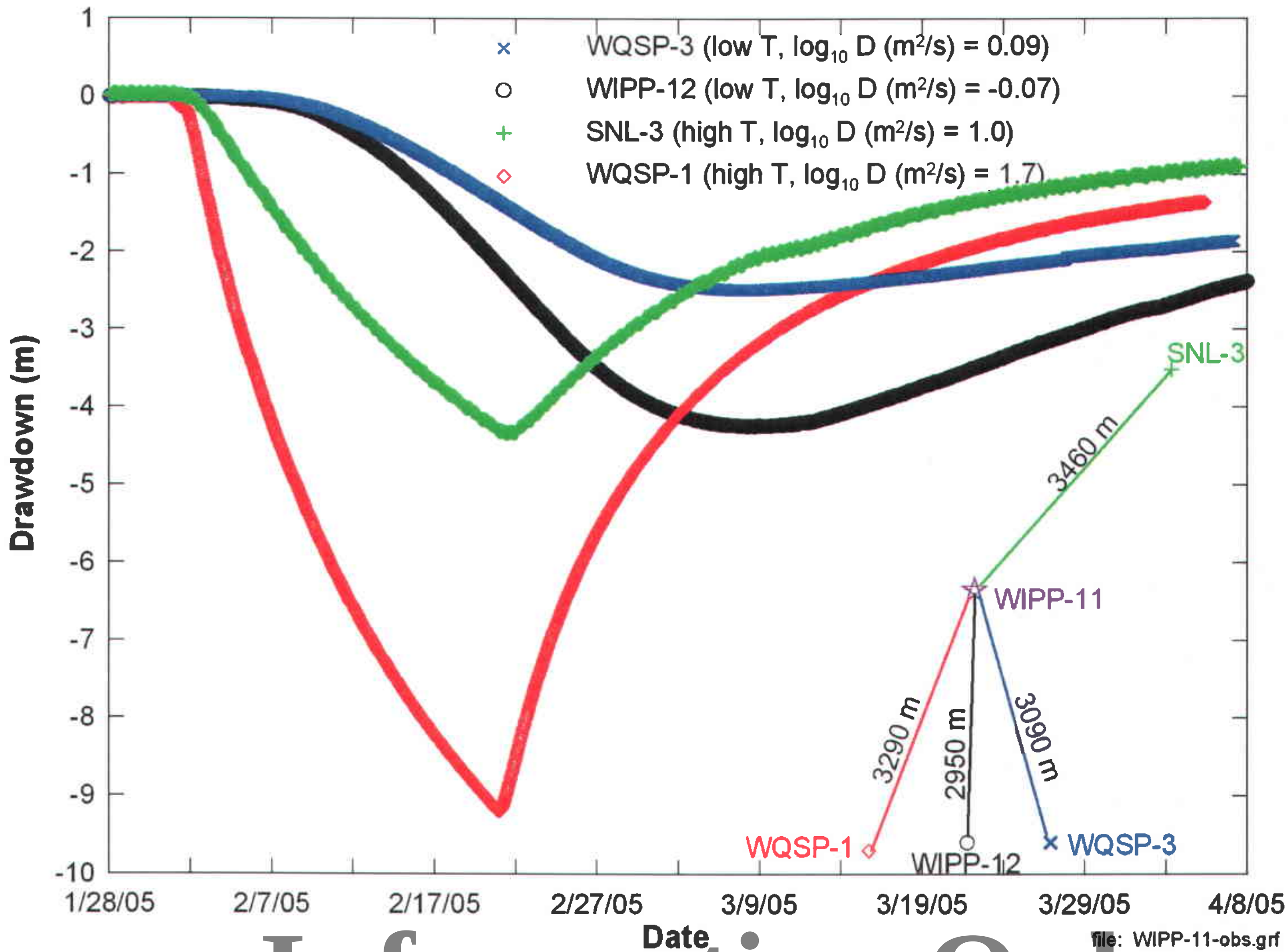
Drawdown Responses in Fractured and Unfractured Zones (1)



Drawdown Responses in Fractured and Unfractured Zones (2)



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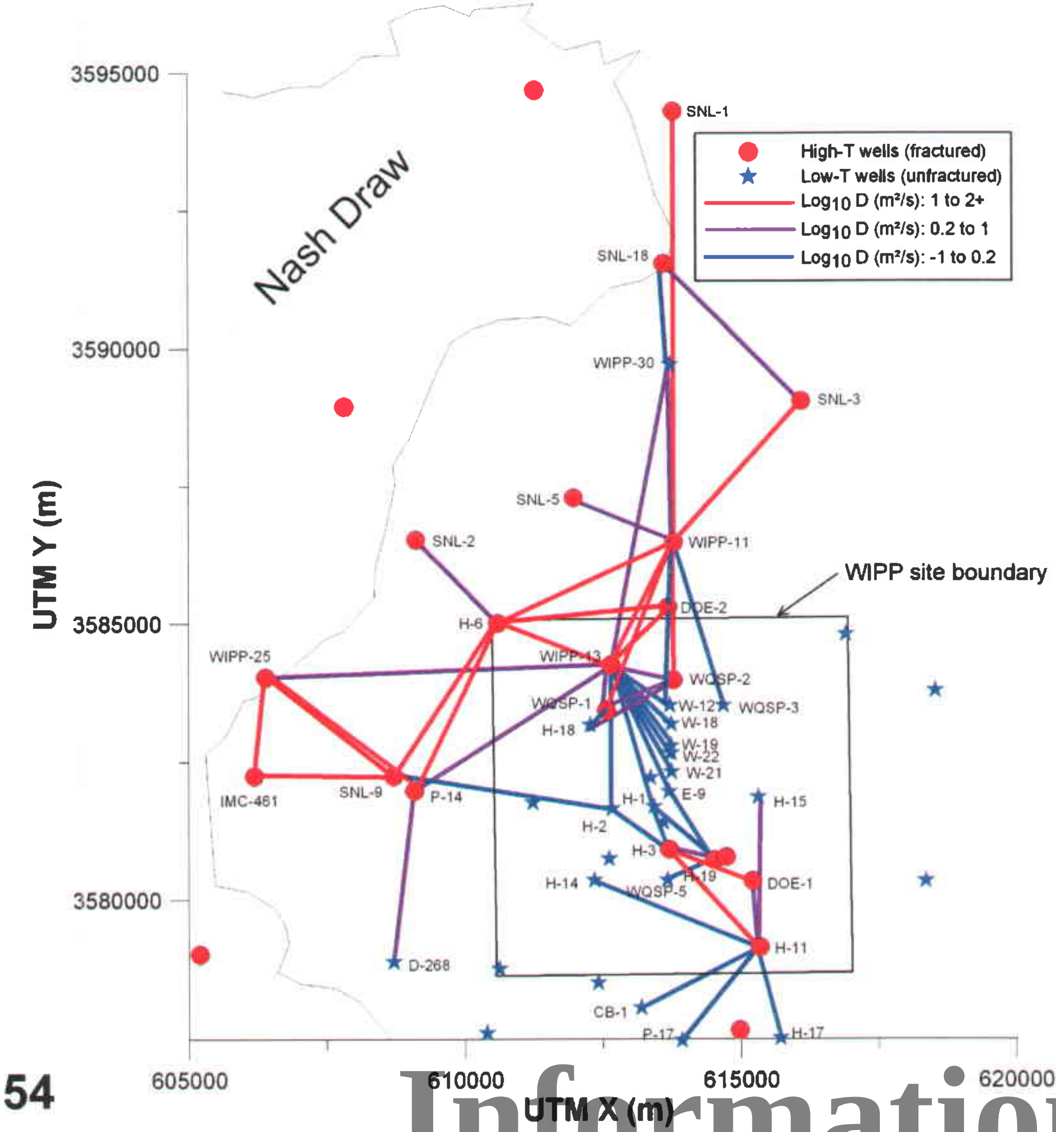
Inferred Diffusivity Values (1)



- Log_{10} D values < 0.2 reflect unfractured conditions
- Log_{10} D values ≥ 0.2 reflect fracture connections
- NE-SW band across the WIPP site shows no evidence of fracturing

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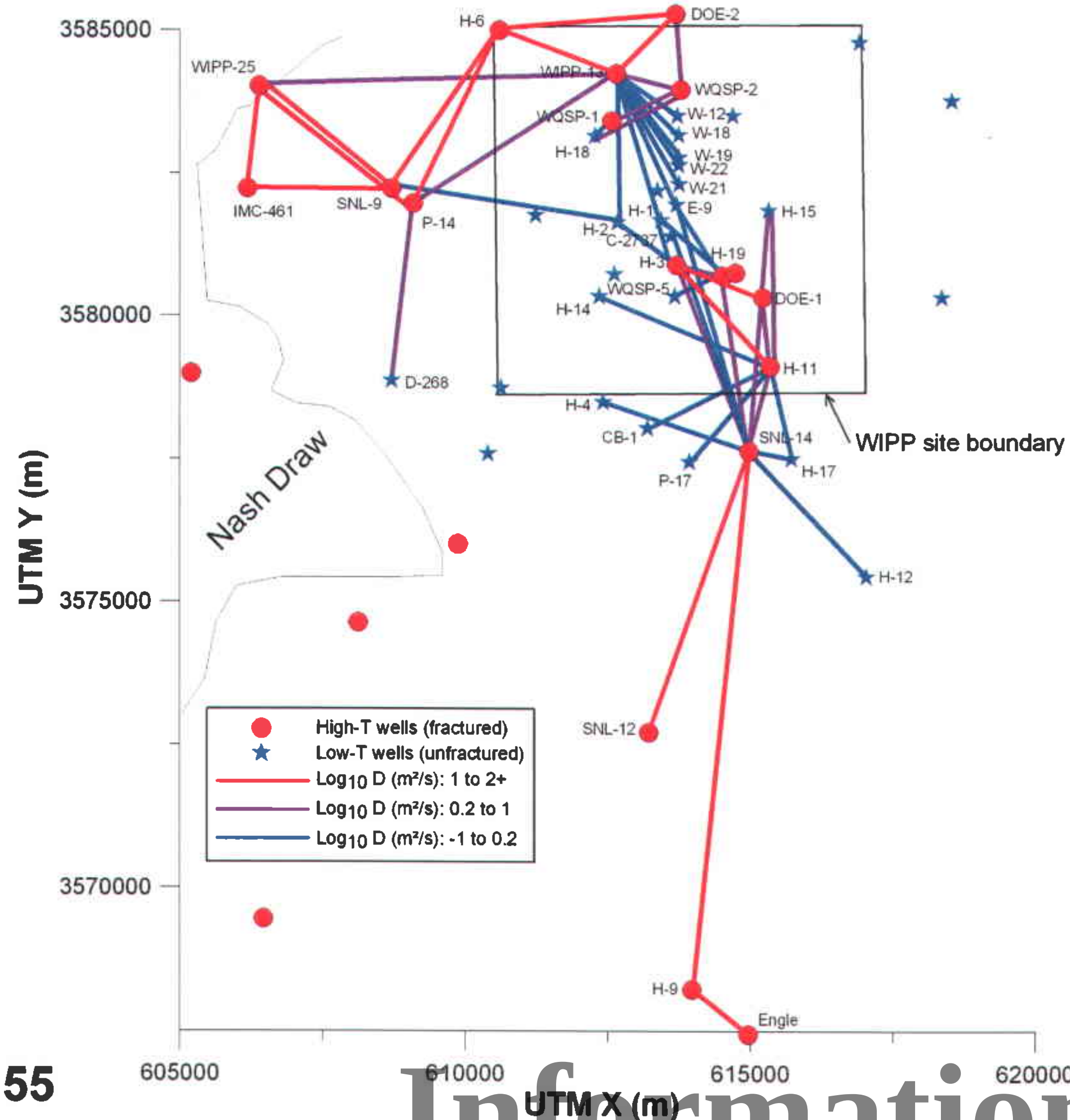
Inferred Diffusivity Values (2)



- Clear indications of continuous high-T (fractured) pathway from the SE WIPP site to the south

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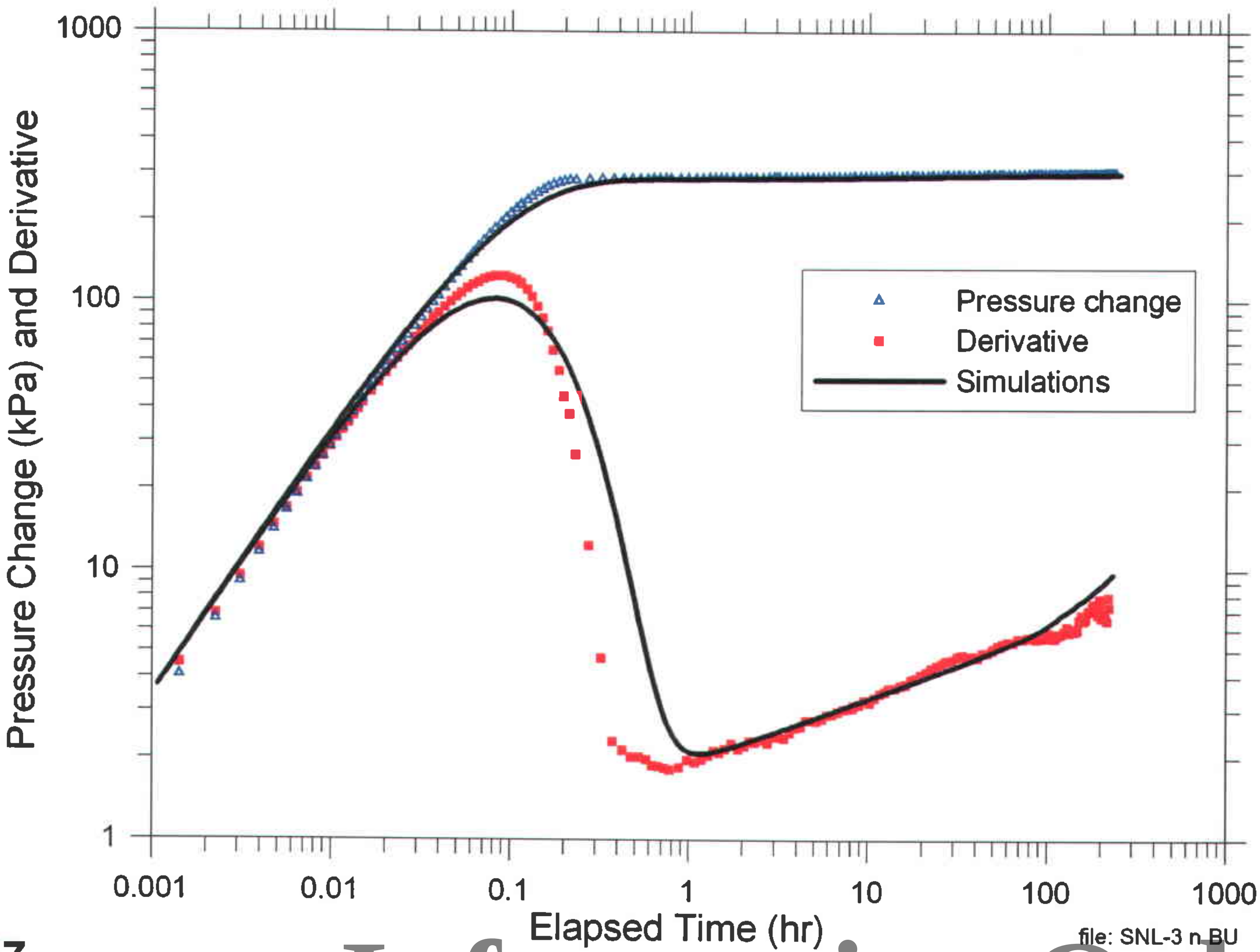
Dimensionality of Flow

Many tests show steadily increasing late-time derivatives as would be caused by a subradial flow dimension

- Option 1: analyze as subradial system—implication is high T
- Option 2: analyze as radial system that rapidly encounters heterogeneities
- Observation: pad-scale responses show "radial-type" behavior on ~100-m scale, then effects of heterogeneities

Flow Dimension Approach



- **Assume well is embedded in system with flow dimension of 1.34**
- **T = 1.9 m^2/s**

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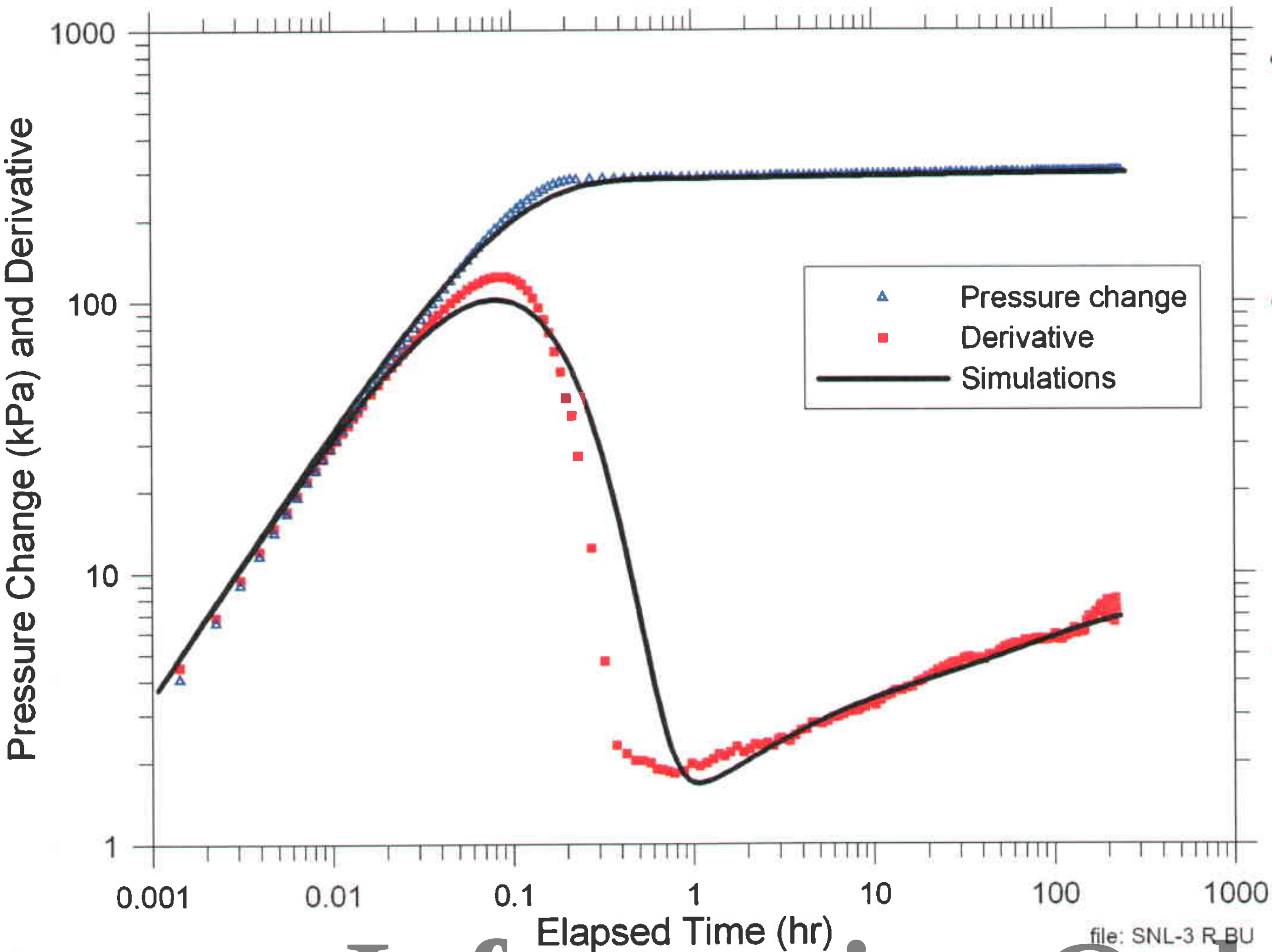
Radial with Heterogeneities Approach



- Assume flow is initially radial (for ~1 hr)
- Pressure transient then encounters area(s) of reduced T
- Near-well T = 1E-3 m^2/s

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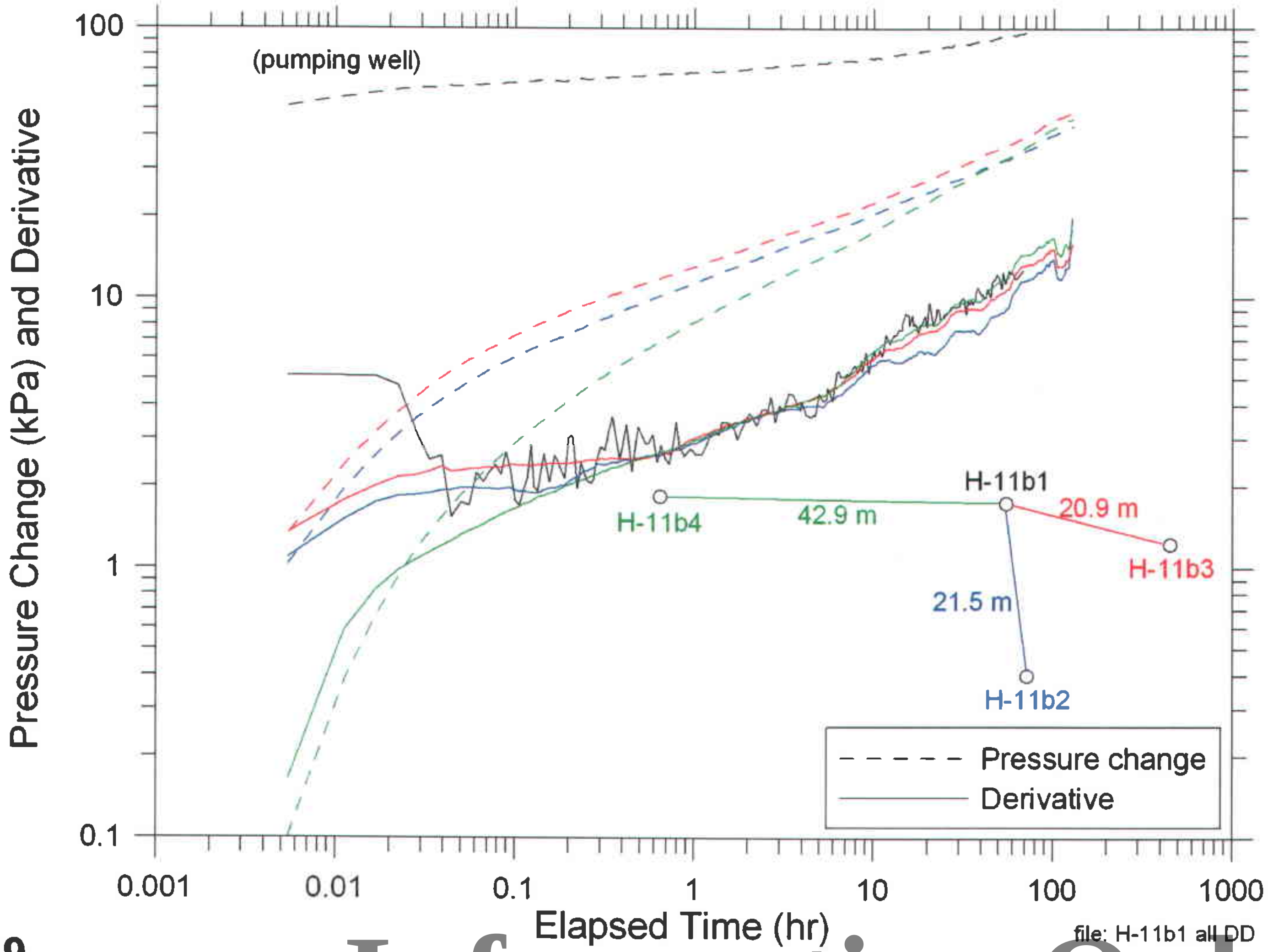
Responses on Hydropad Scale



- **H-11b1 pumping test**
- **All wells shows same subradial derivative behavior after ~1 hr**
- **Can't be single fracture**

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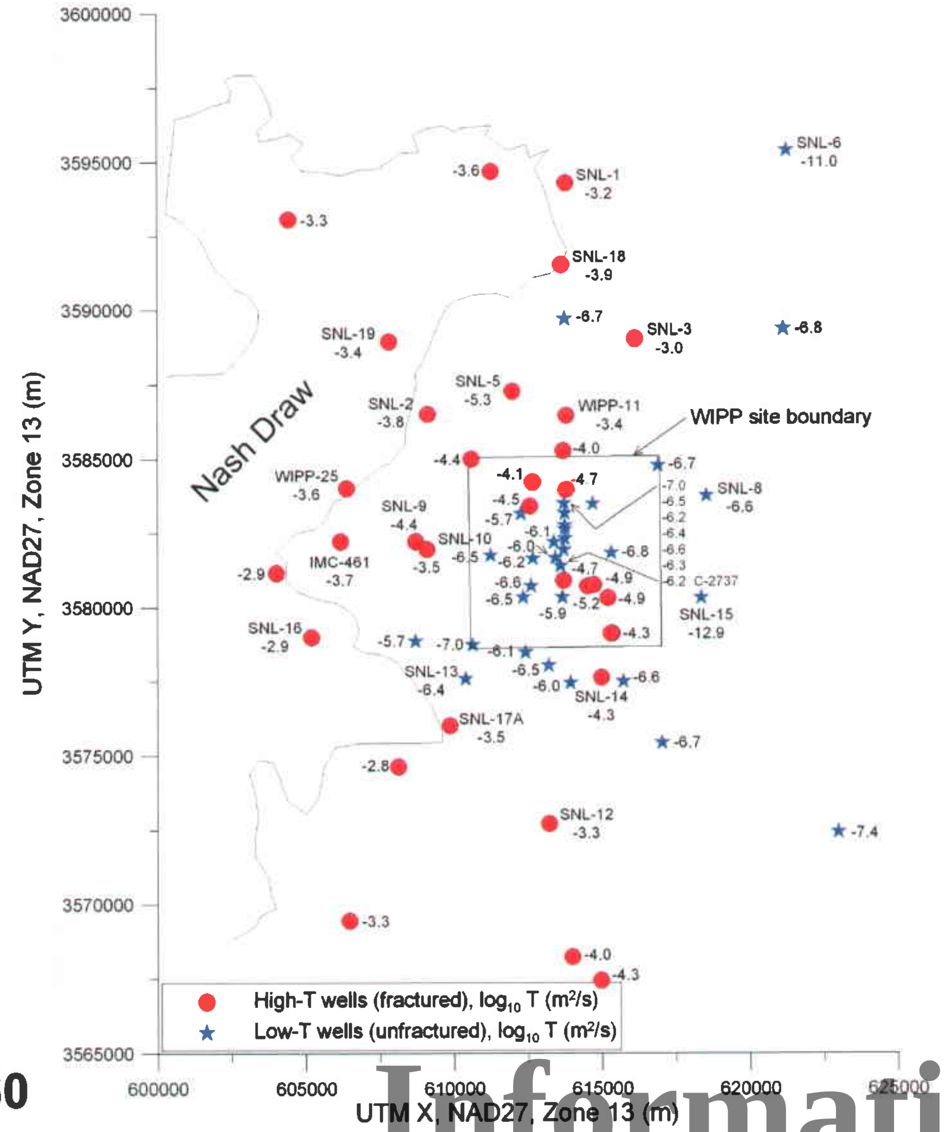
Culebra Heterogeneity



- Outside of Nash Draw, any pressure transient propagating away from a high-T well will encounter lower T
- This results in “channeling” of responses and apparent subradial flow dimensions

Conclusions on Dimensionality of Flow

- On the 100-m (hectometer) scale, flow is best represented as "radial" (space-filling)
- On the kilometer scale, heterogeneities are encountered that result in apparent non-radial flow dimensions

Monitoring

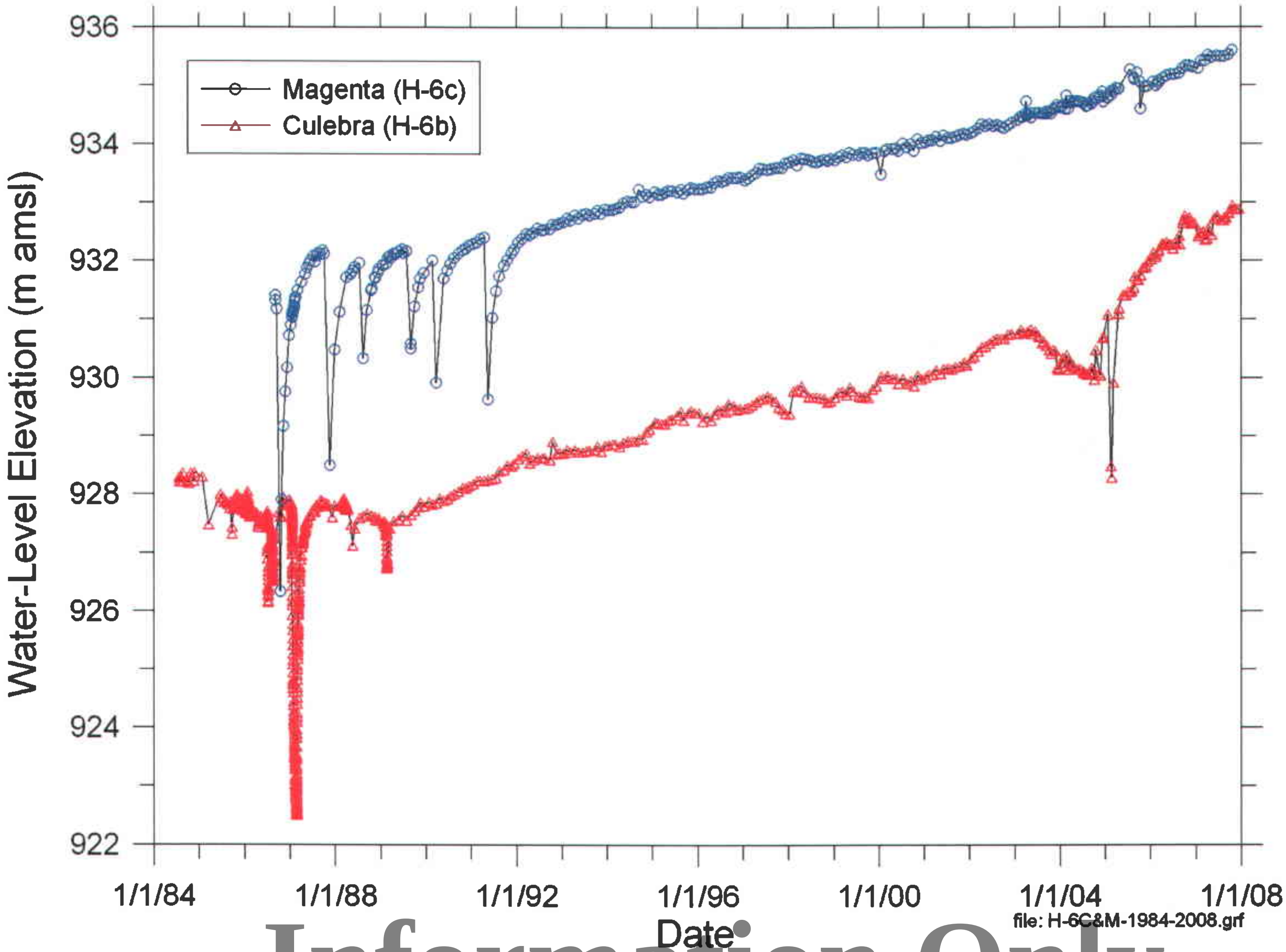
Monitoring

- Monthly water levels measured since 1977
- Occasional high-frequency monitoring with transducers performed since ~1980, usually associated with testing
- Beginning in 2002, gradual instrumentation of all wells with Trolls that make hourly pressure readings

Monitoring Observations

- General rise in both Culebra and Magenta water levels over last 2 decades
- Spikes in water level from one month to the next with rapid fall-off
- Responses to major rainfall events at wells in Nash Draw
- Slow equilibration with very high heads east of WIPP

Culebra and Magenta Long-Term Rising Water Levels



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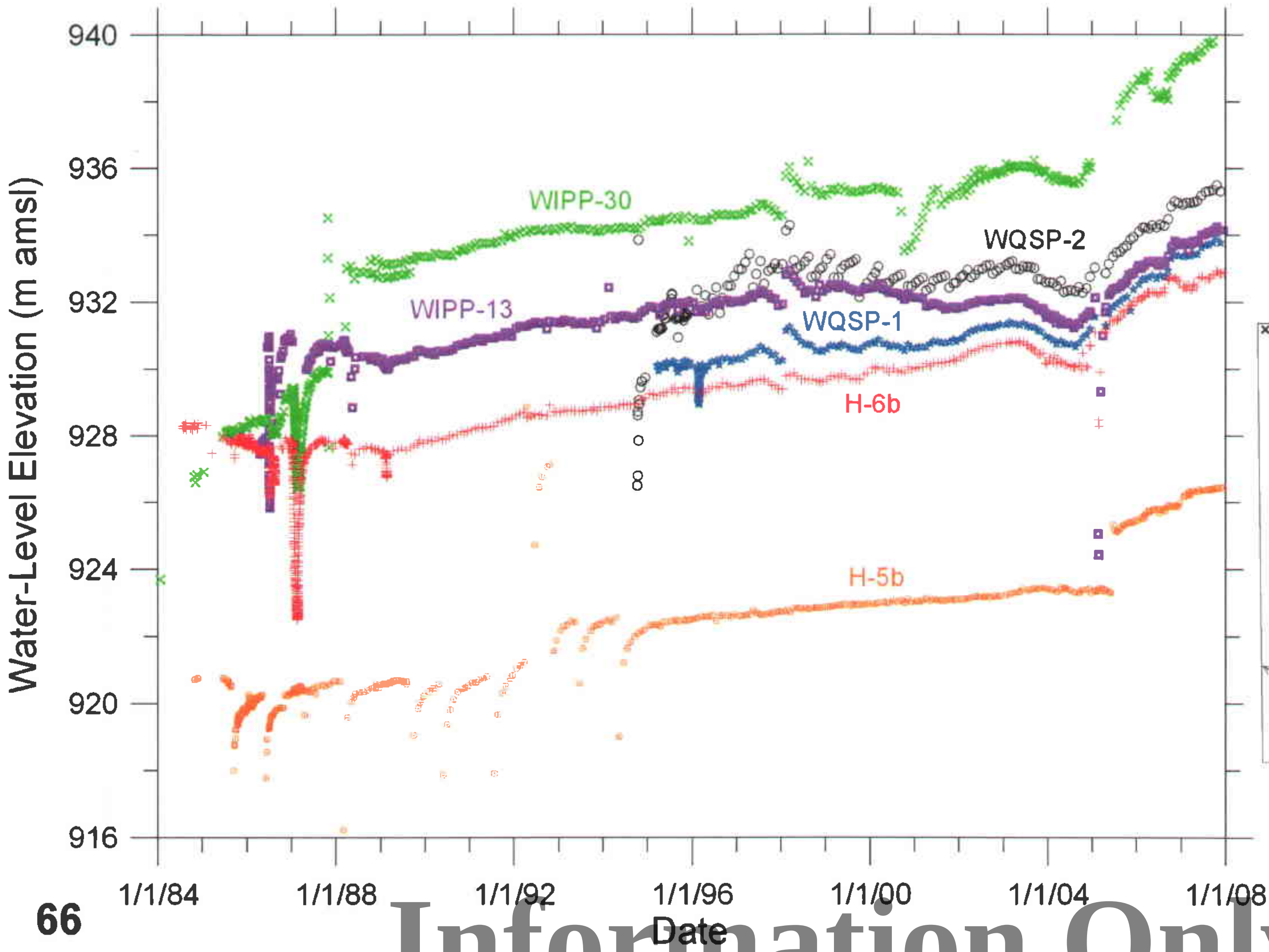
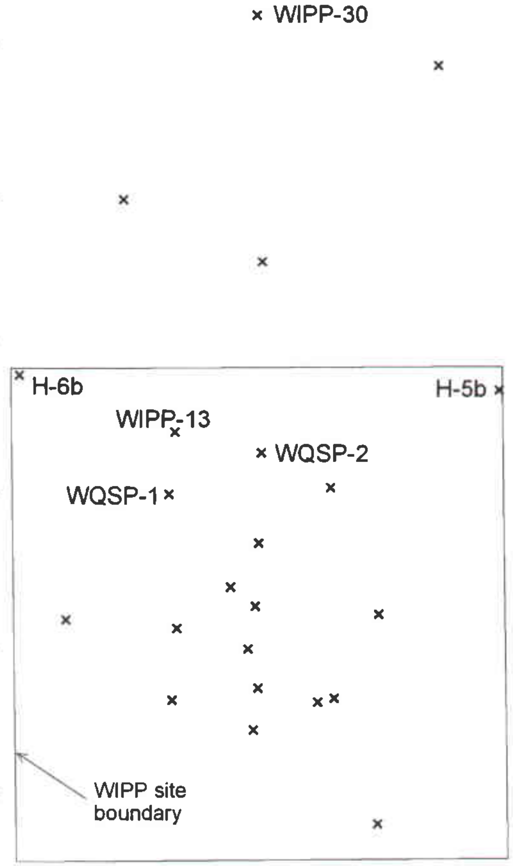
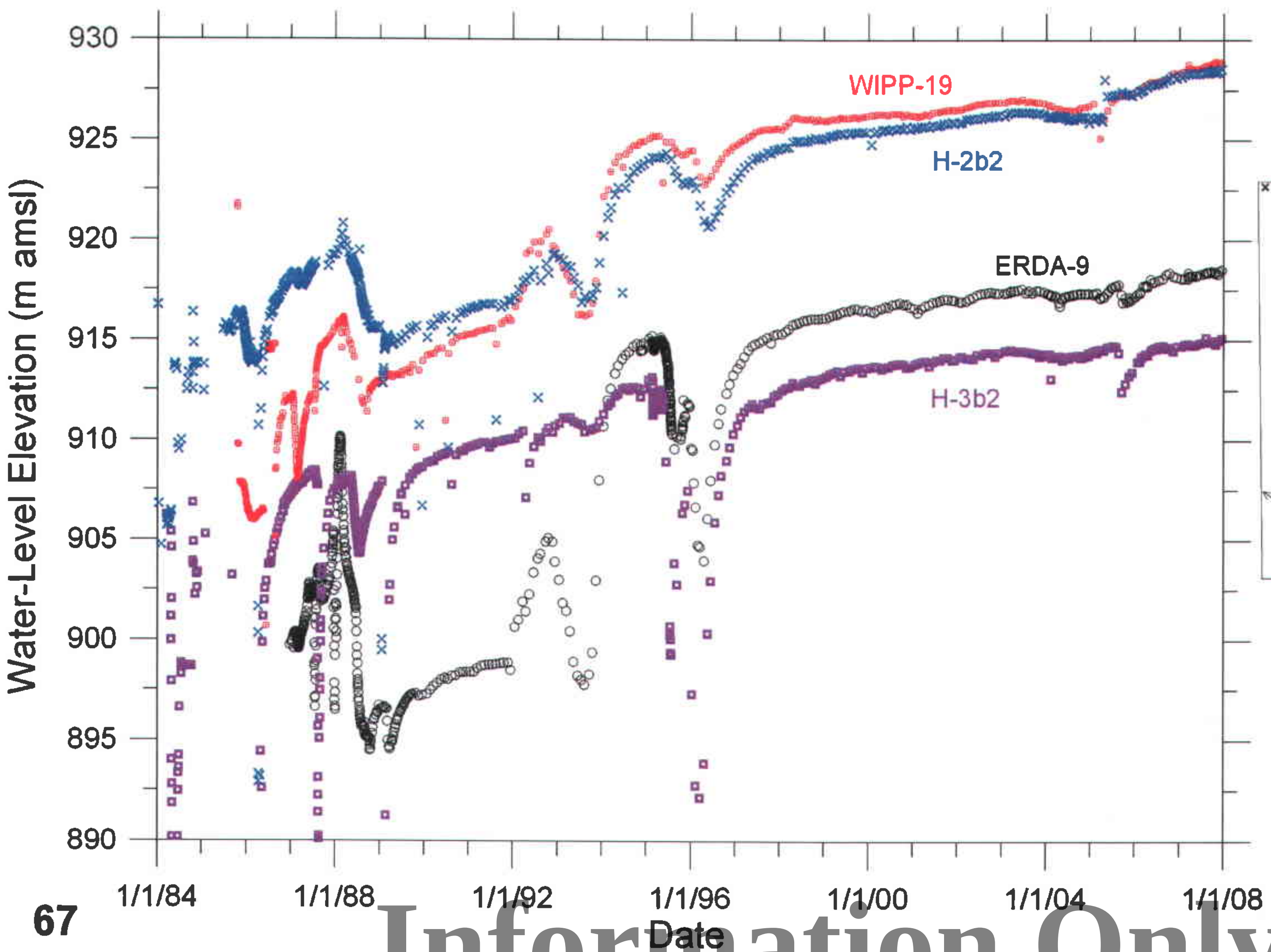
Culebra Long-Term Rising Water Levels (1)

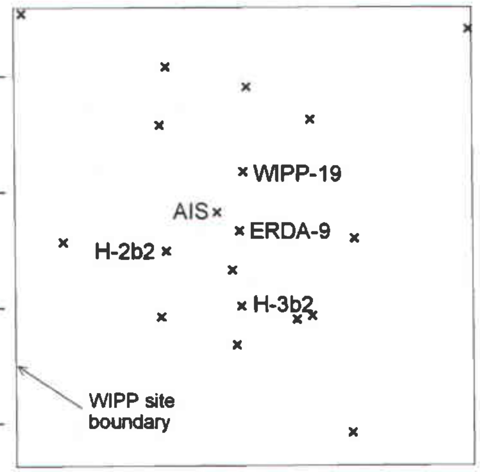




Information Only

Culebra Long-Term Rising Water Levels (2)





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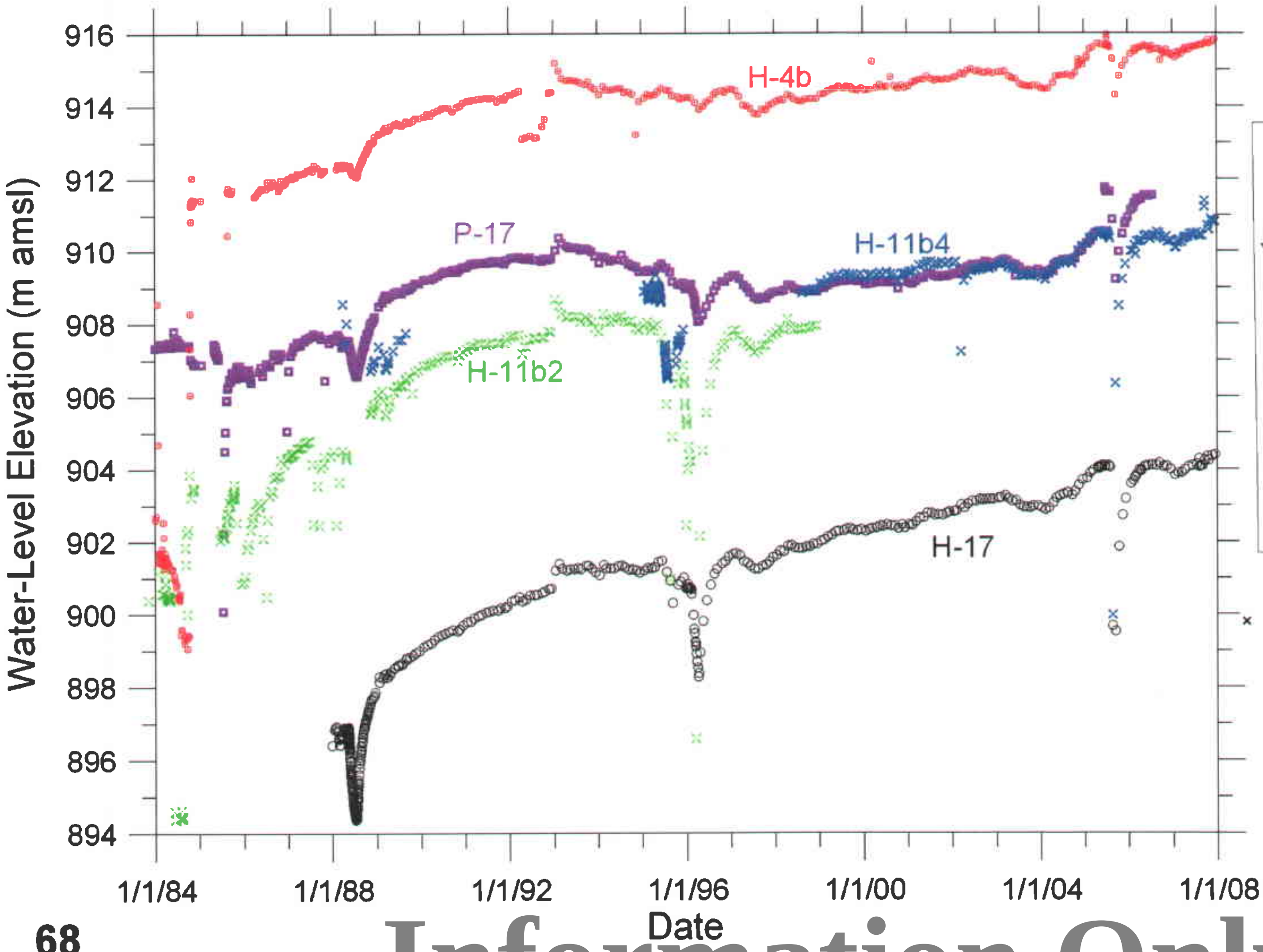
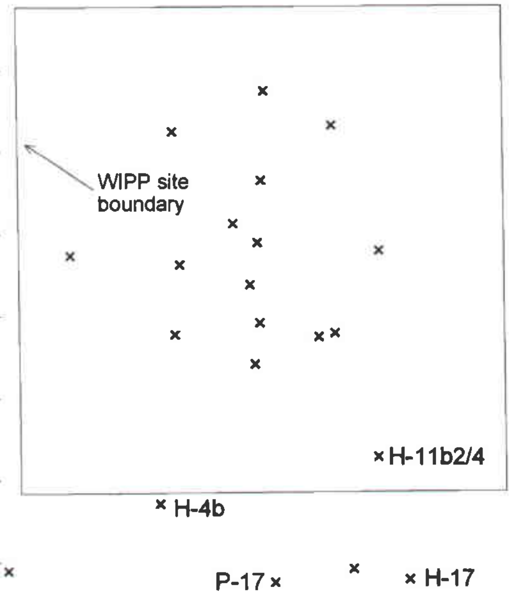
Culebra Long-Term Rising Water Levels (3)





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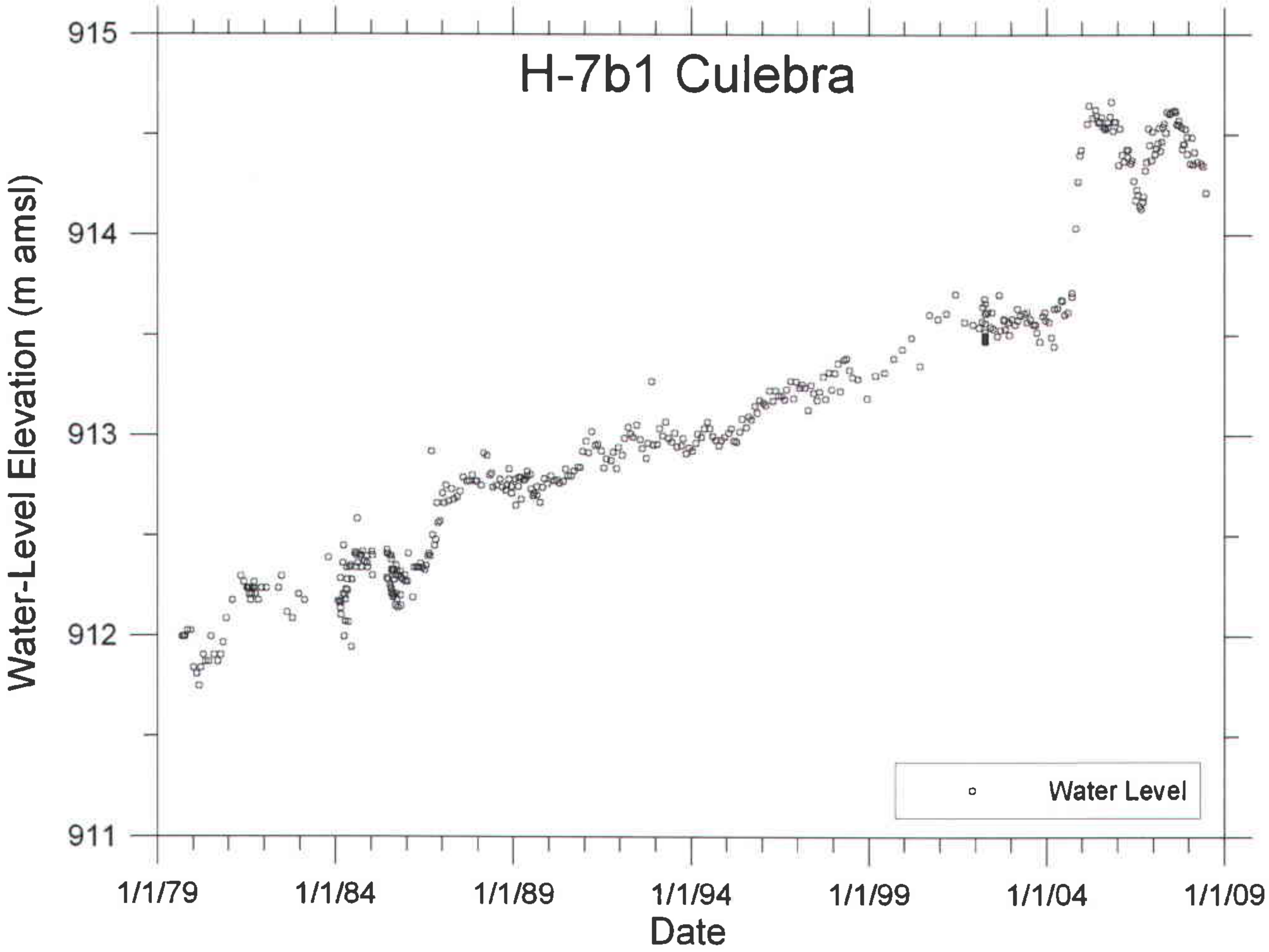
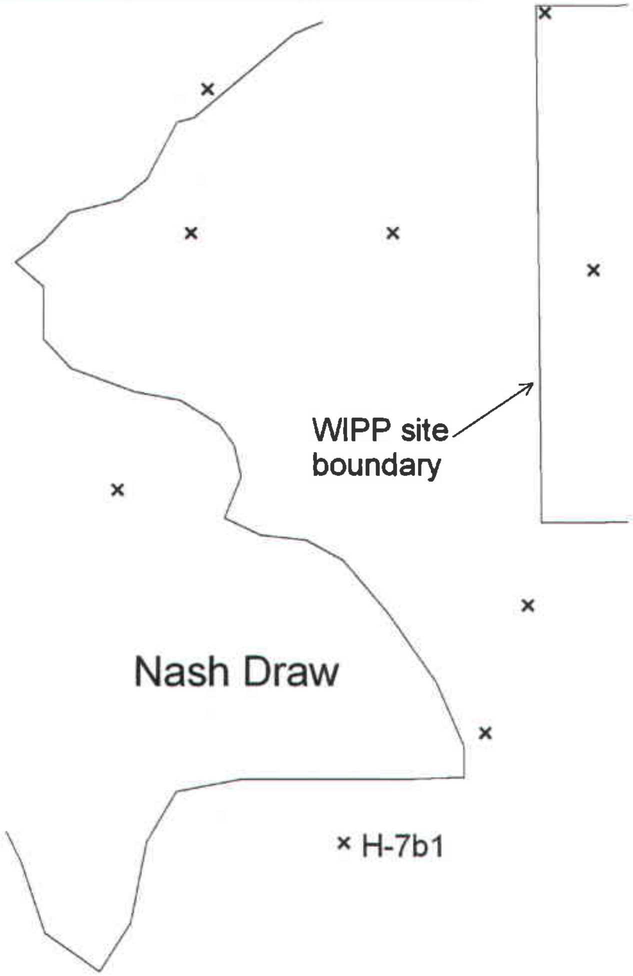
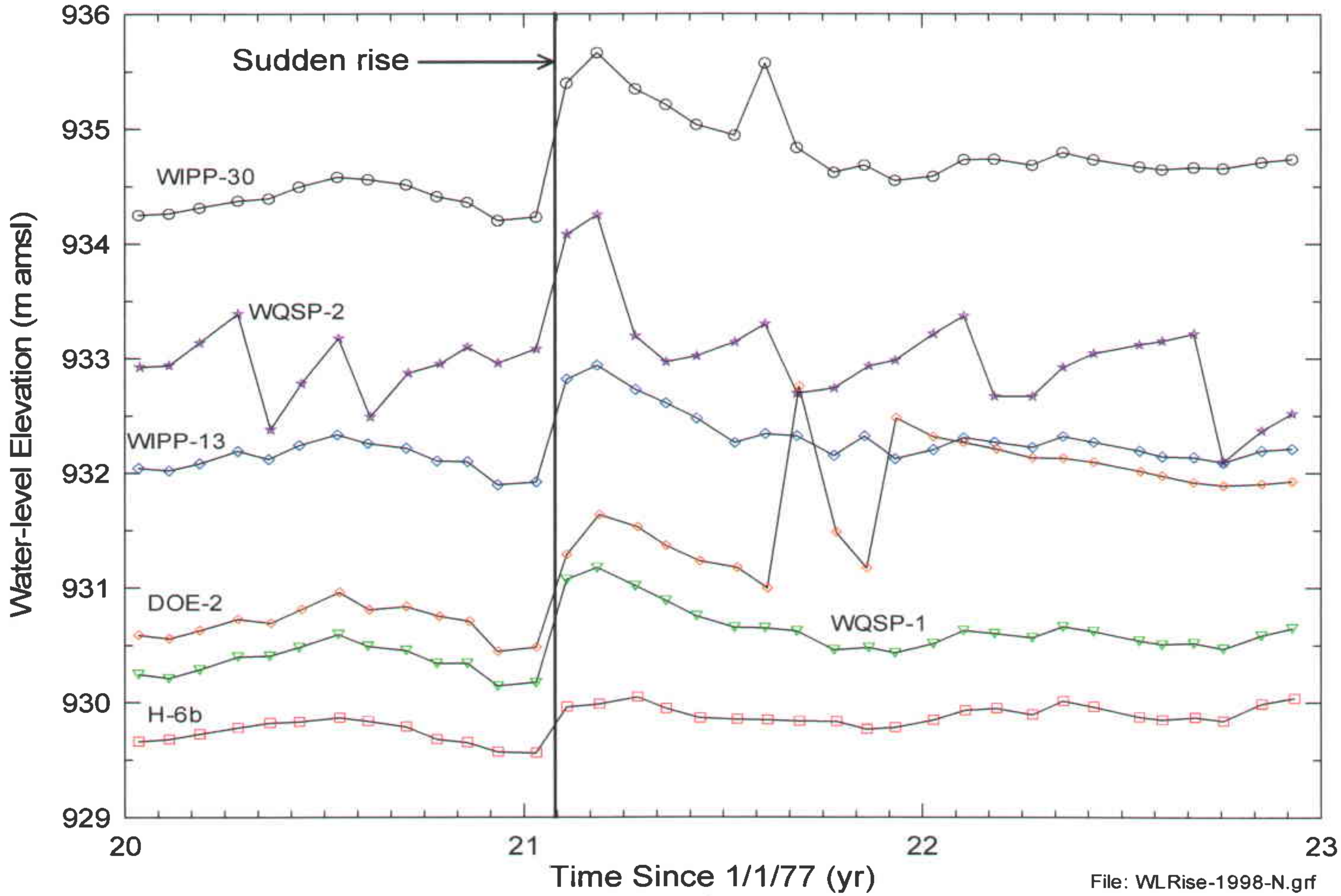
Culebra Long-Term Rising Water Levels (4)





Sudden Water-Level Fluctuations (1)

1998 Water-Level Rise North of WIPP



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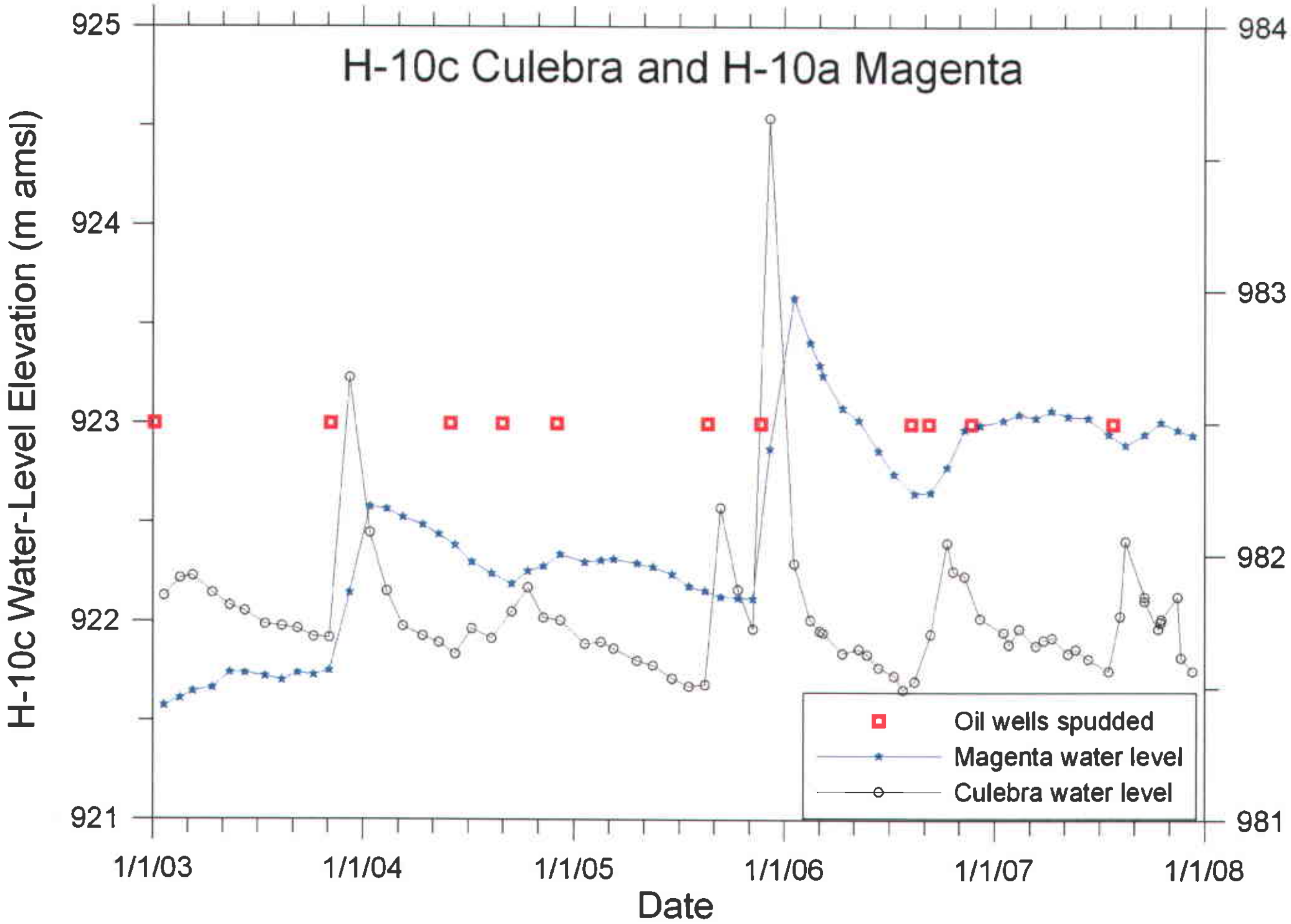
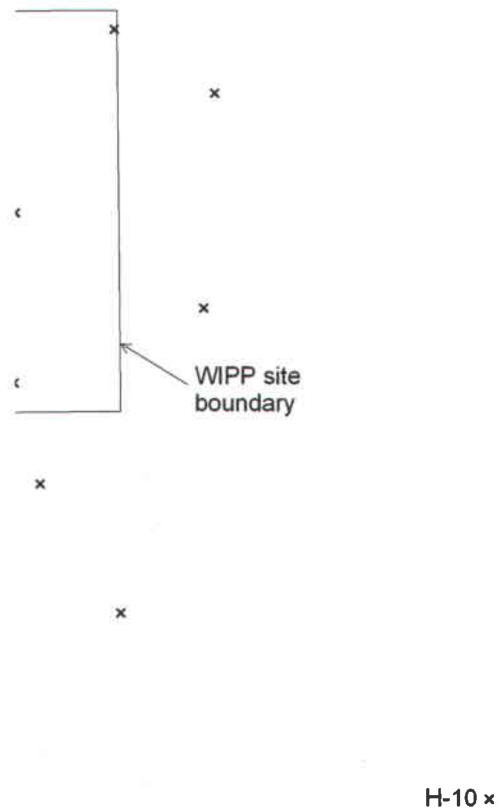
Sudden Water-Level Fluctuations (2)





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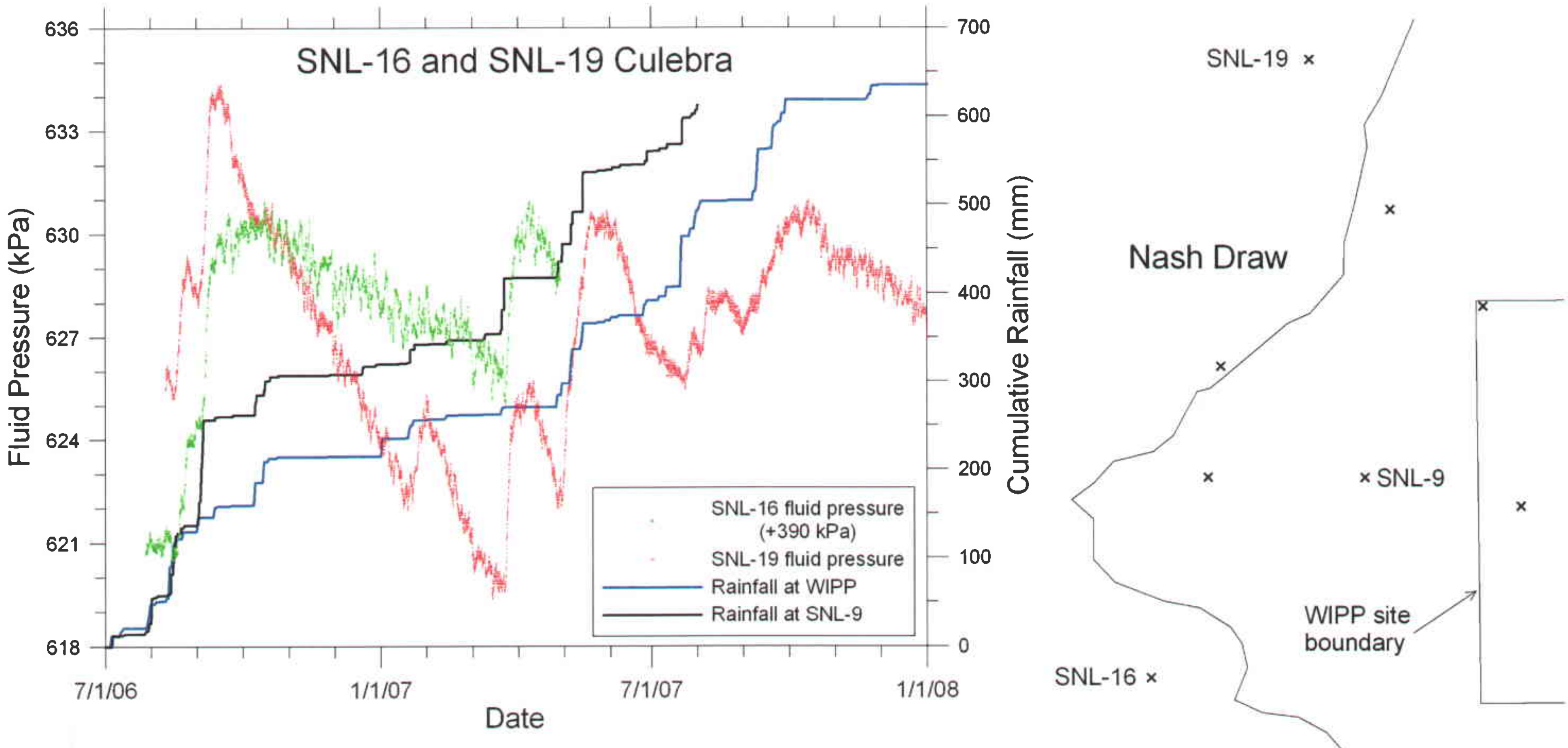
Water-Level Responses to Rainfall (1)



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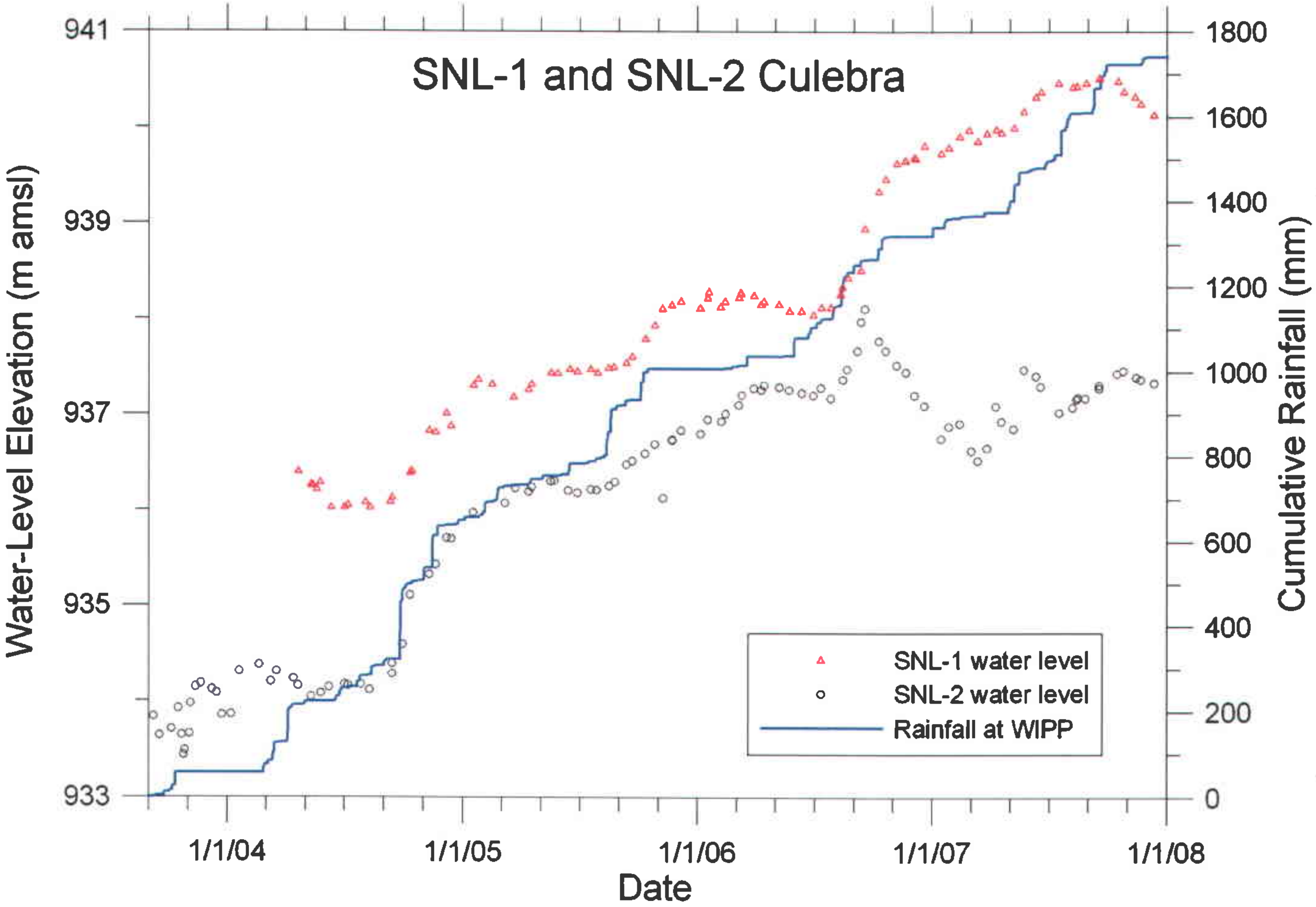
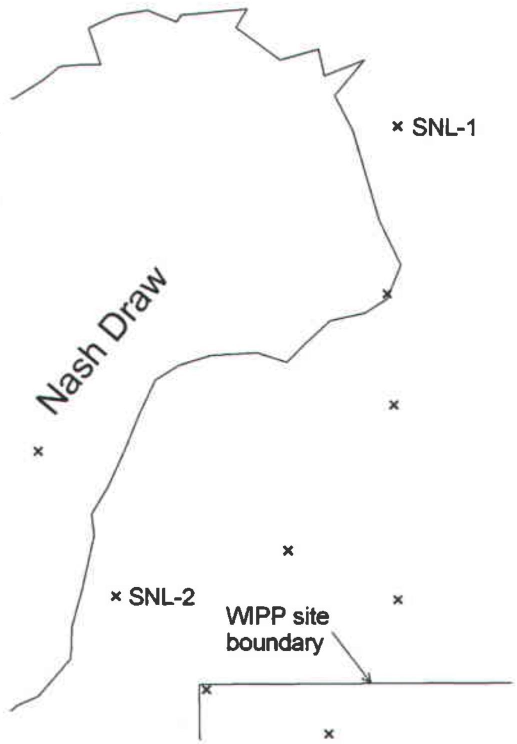
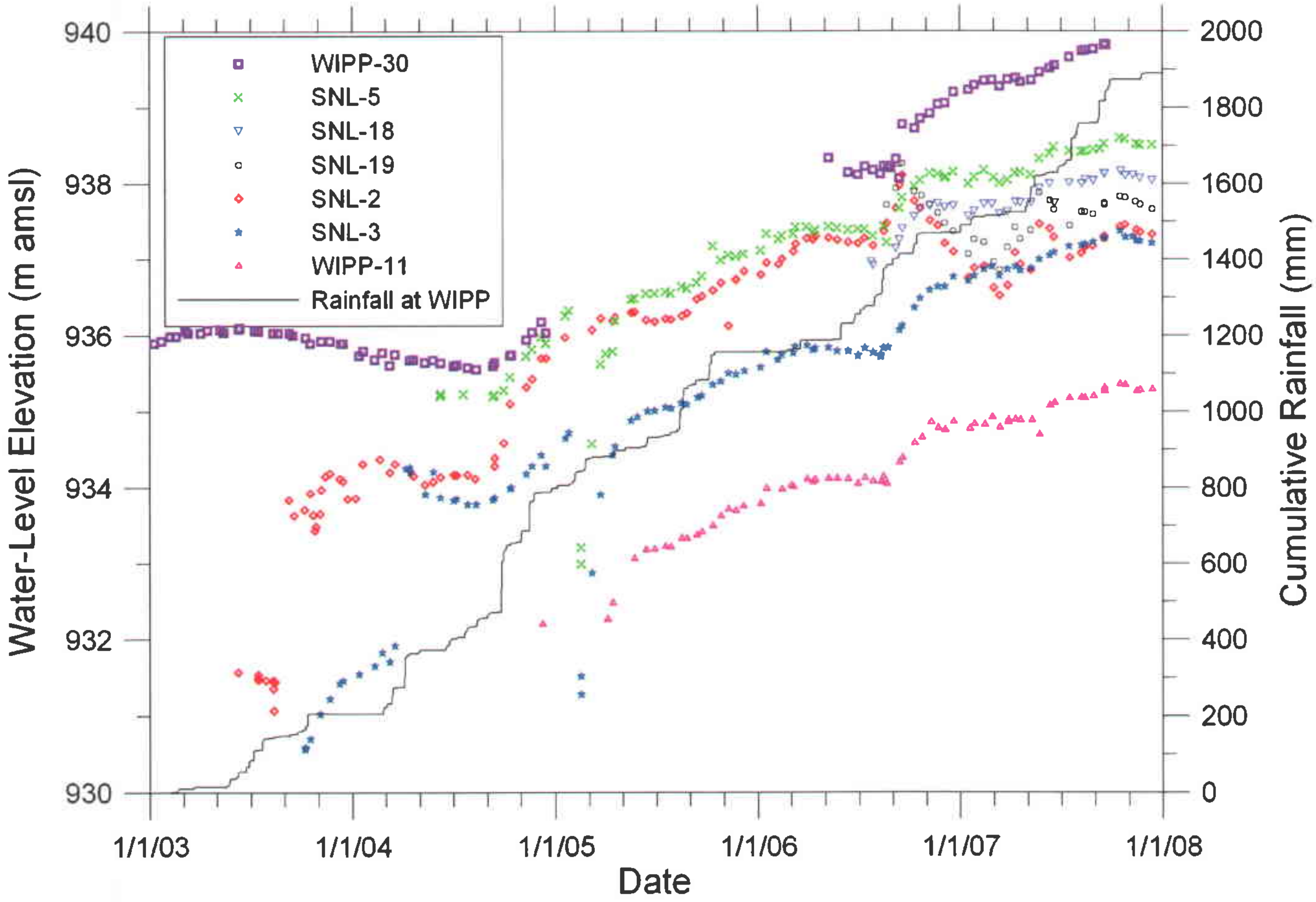
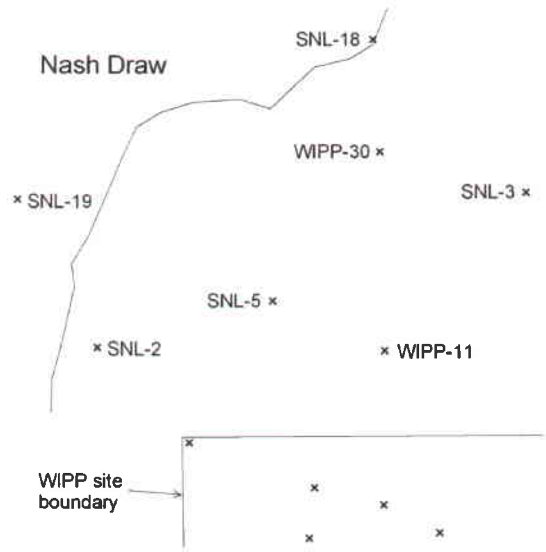
Water-Level Responses to Rainfall (2)





Water-Level Responses to Rainfall (3)





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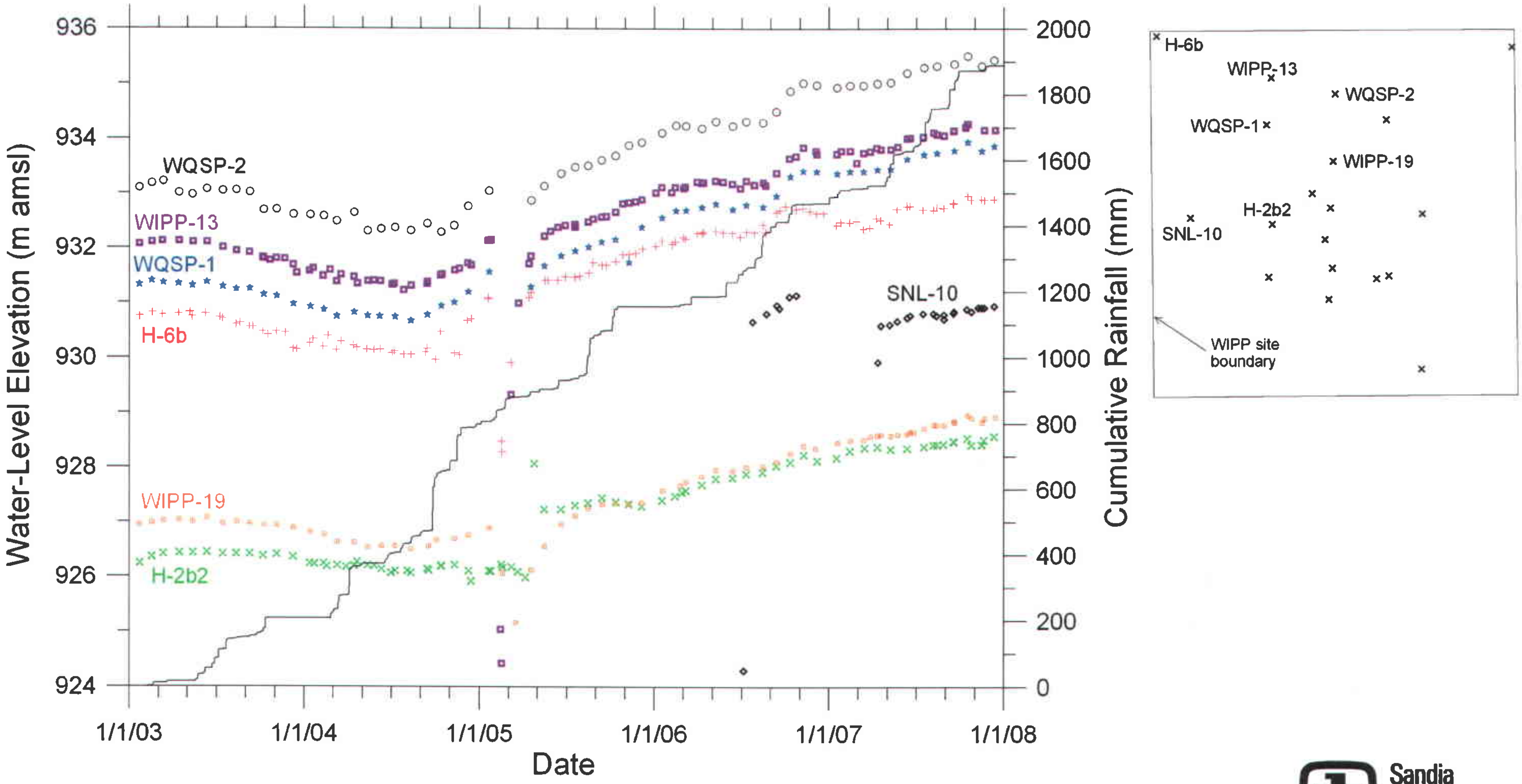
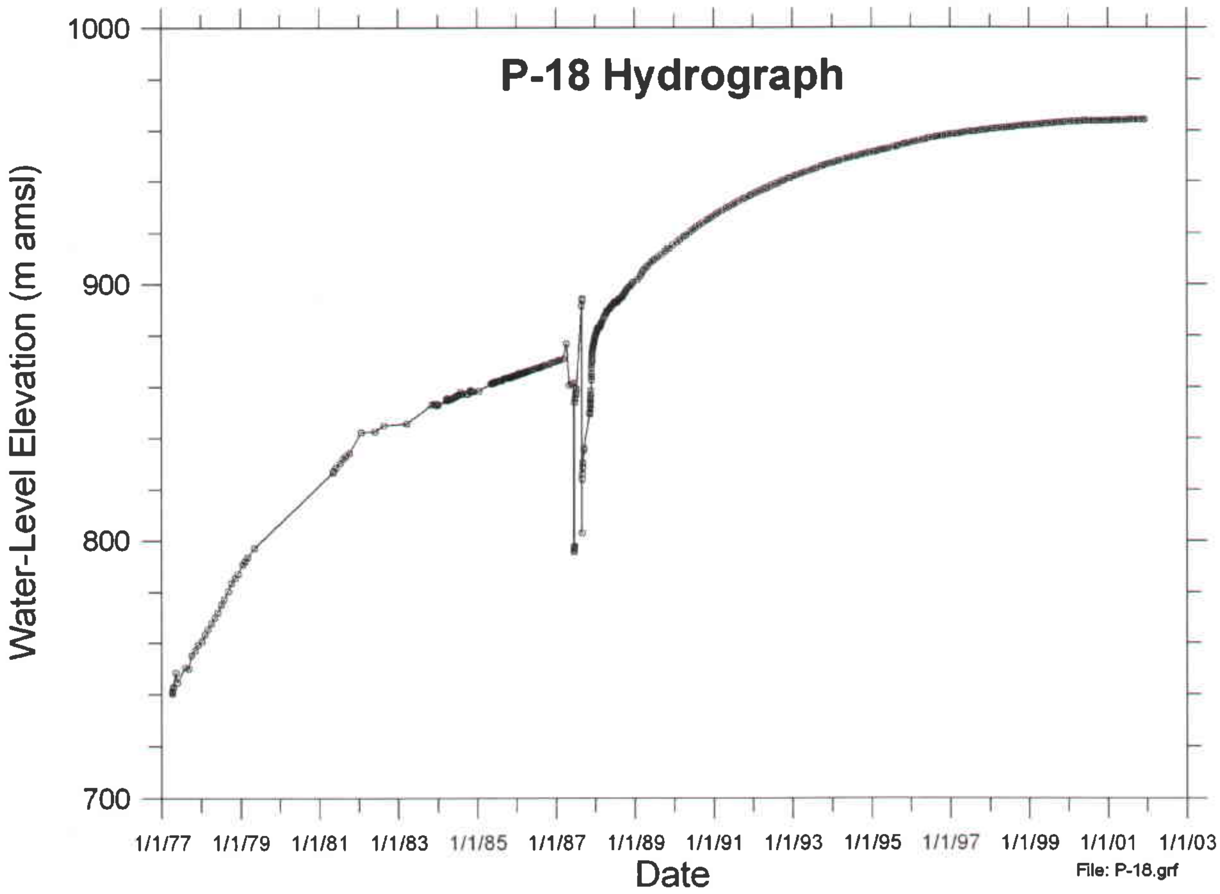
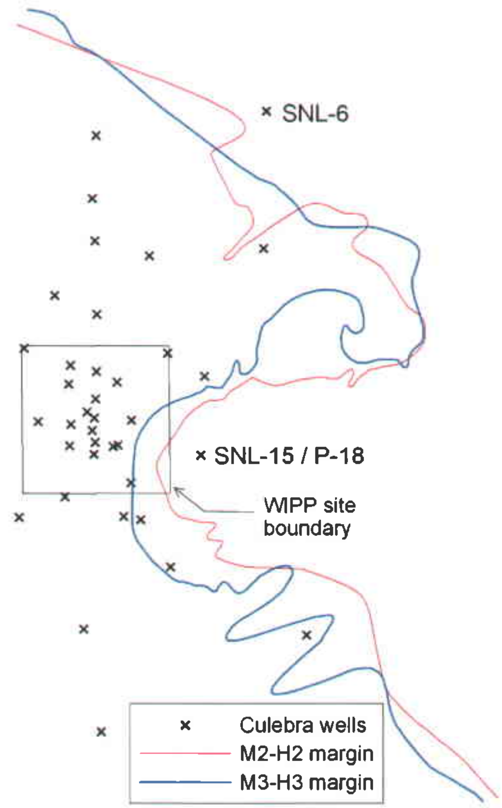
Water-Level Responses to Rainfall (4)



Slow Equilibration with High Heads (1)

Culebra is sandwiched between halite beds east of M2-H2 margin and contains halite cements





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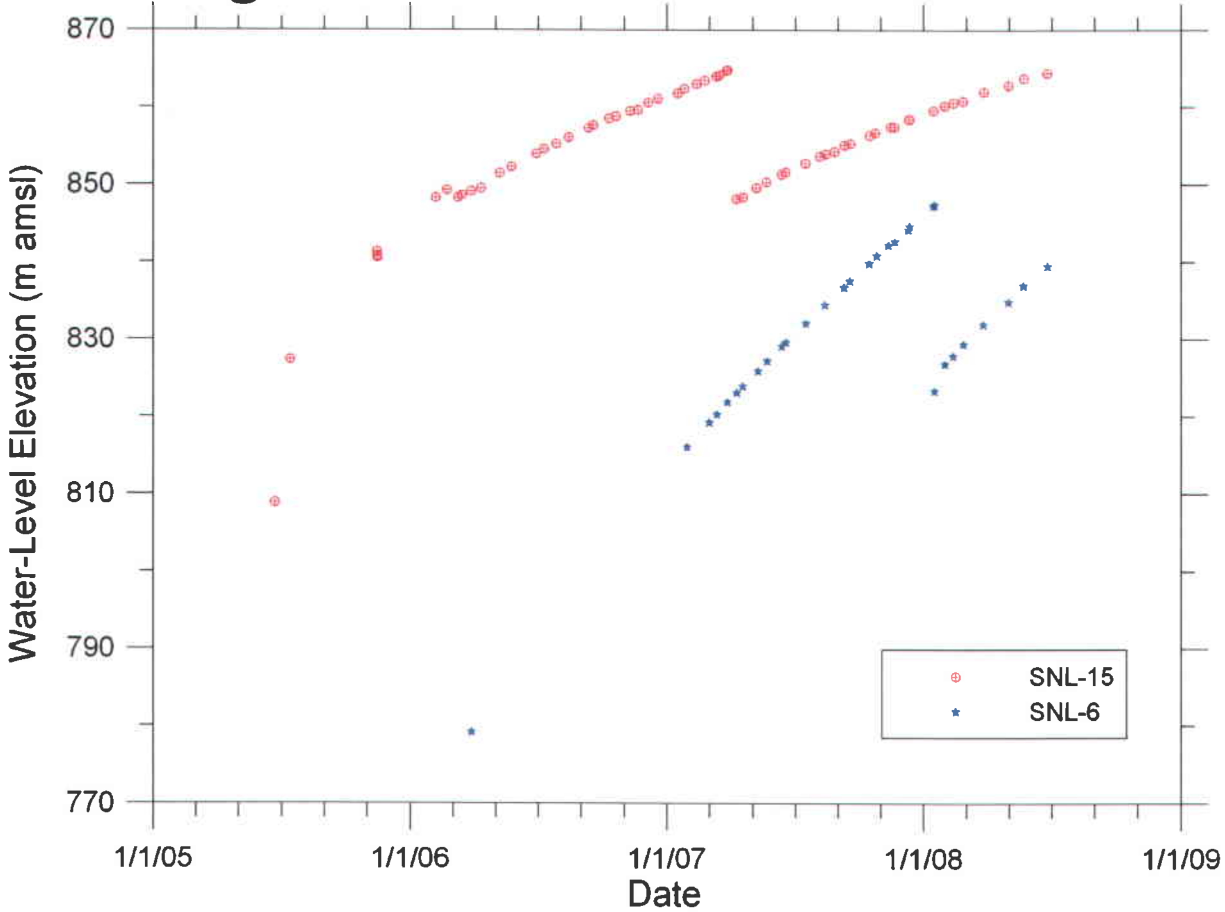
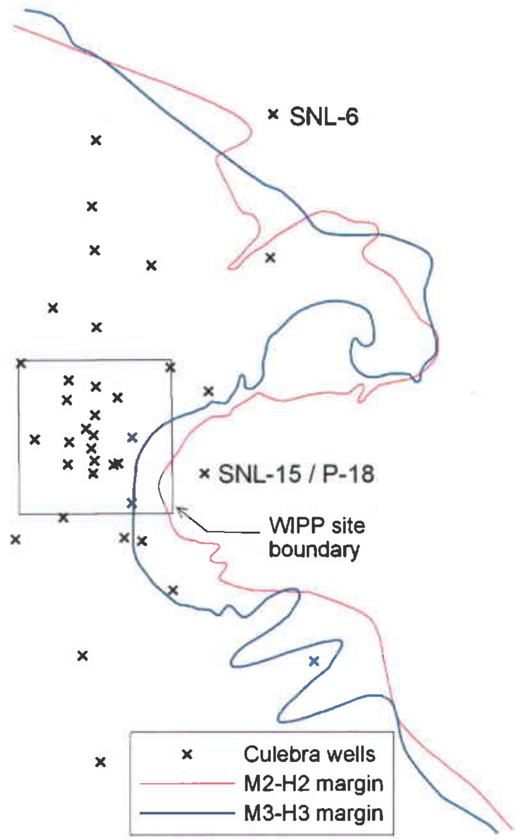
Slow Equilibration with High Heads (2)

Simulations suggest heads will stabilize above ground surface in centuries





Evaluation of Long-Term Water-Level Rise

Evaluation of Long-Term Water-Level Rise

- The hydrologic system at WIPP was originally conceptualized as being in steady state, perturbed only by anthropogenic activities—well drilling and testing, shaft sinking, etc.
- After WIPP-related perturbations largely stopped in ~1989, Culebra and Magenta heads were observed to be rising beyond their predicted steady-state values
- Three potential anthropogenic mechanisms have been identified that could cause water levels to rise

Hypothesized Anthropogenic Causes of Long-Term Water-Level Rise

- Leakage from the Intrepid East tailings pile/ ponds causing locally elevated Culebra and Magenta heads, which propagate to the south
- Leakage between formations through boreholes that are poorly cased or improperly plugged and abandoned
- Leakage of brine injected at depth for secondary oil recovery or salt-water disposal through poorly plugged or cased boreholes

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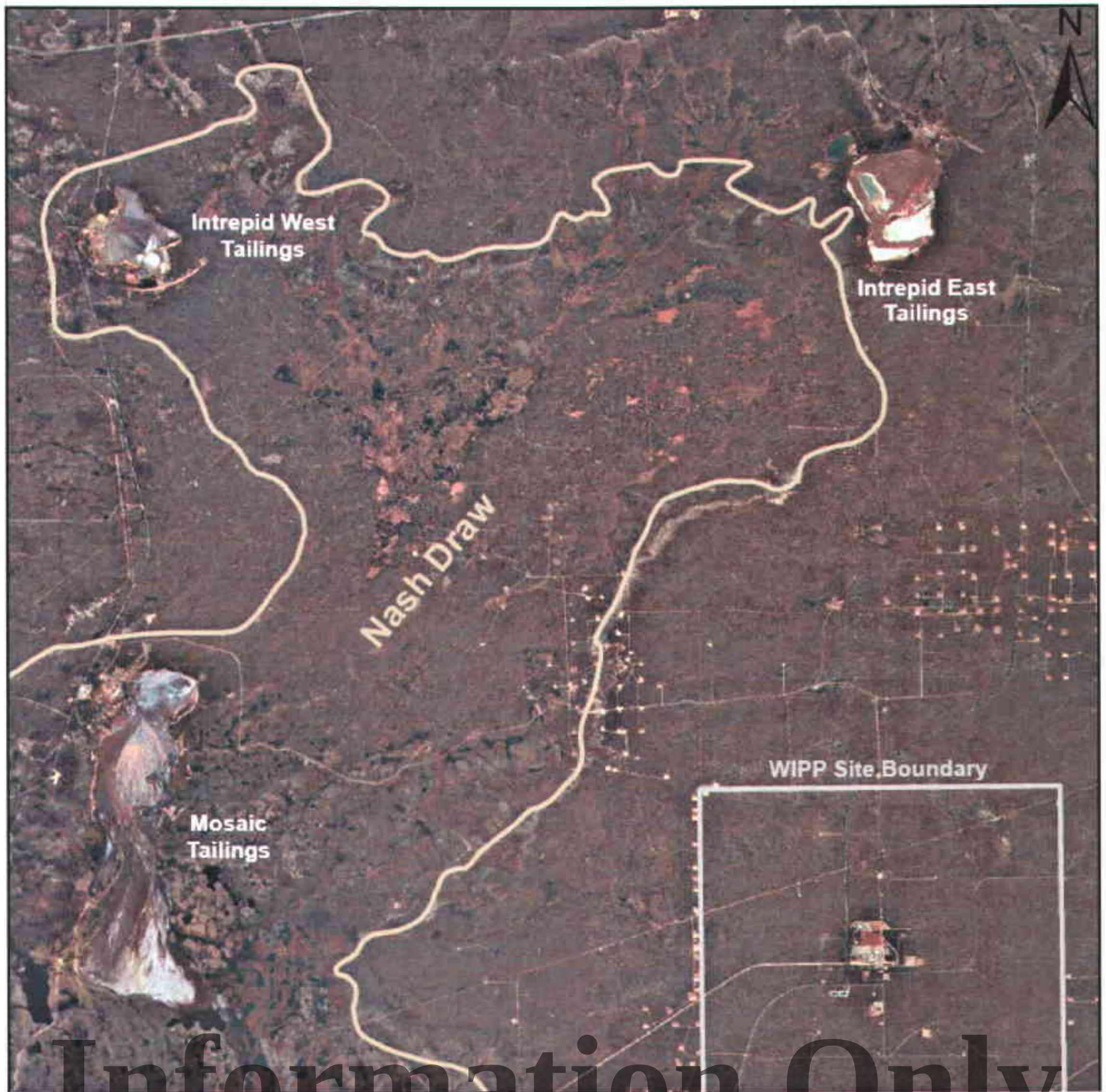
Potash Tailings Piles Near WIPP



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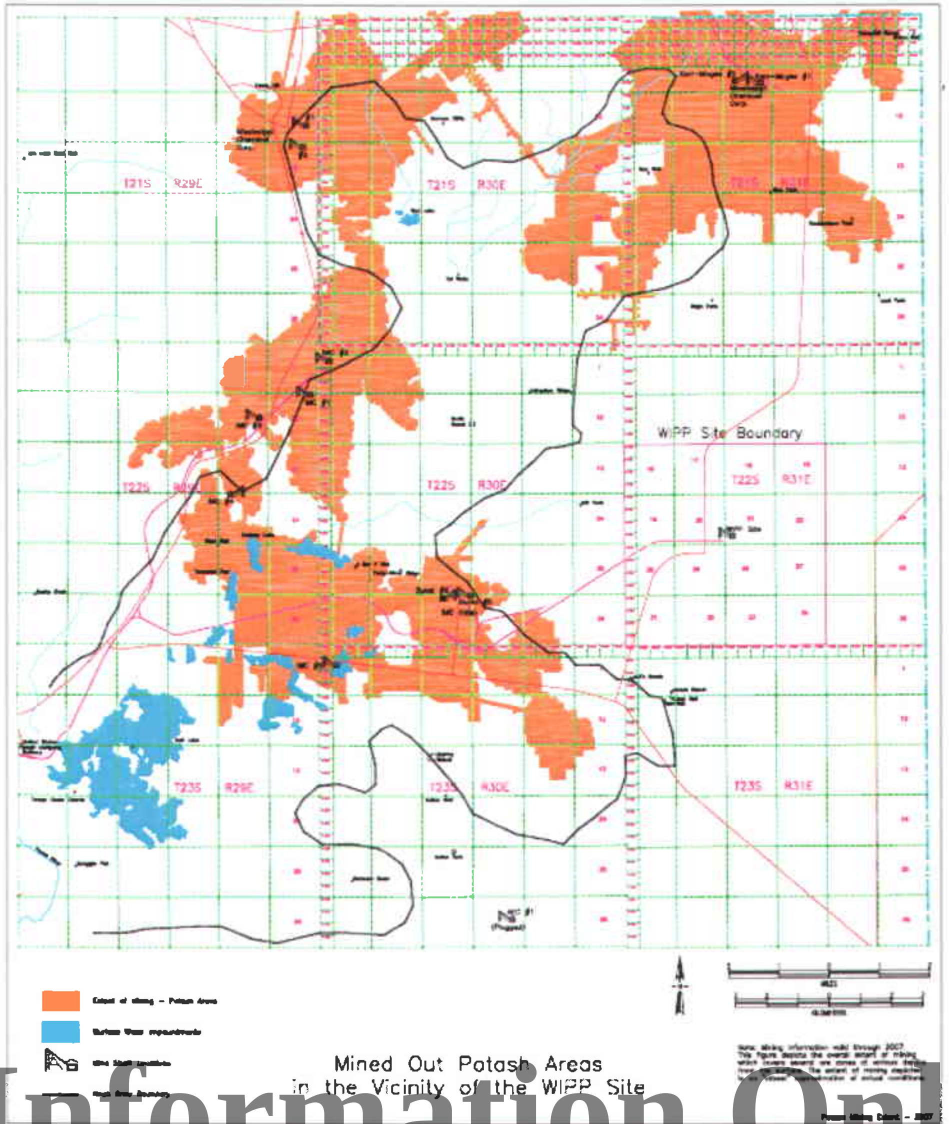
Related Observations

- If Magenta head is also rising, the Magenta is probably not the cause of the rise in the Culebra
- In northern Nash Draw, water is found above the Rustler in the Dewey Lake as well as in karstic Tamarisk and/or Forty-niner
- Water is also found in the Dewey Lake south of the WIPP site
- Potash processing brine was found 11 m below ground surface at SNL-1, immediately south of the Intrepid East tailings pile
- Subsidence related to potash mining may suddenly open pathways for near-surface water to reach Culebra that did not exist before

Potash Mining Around WIPP



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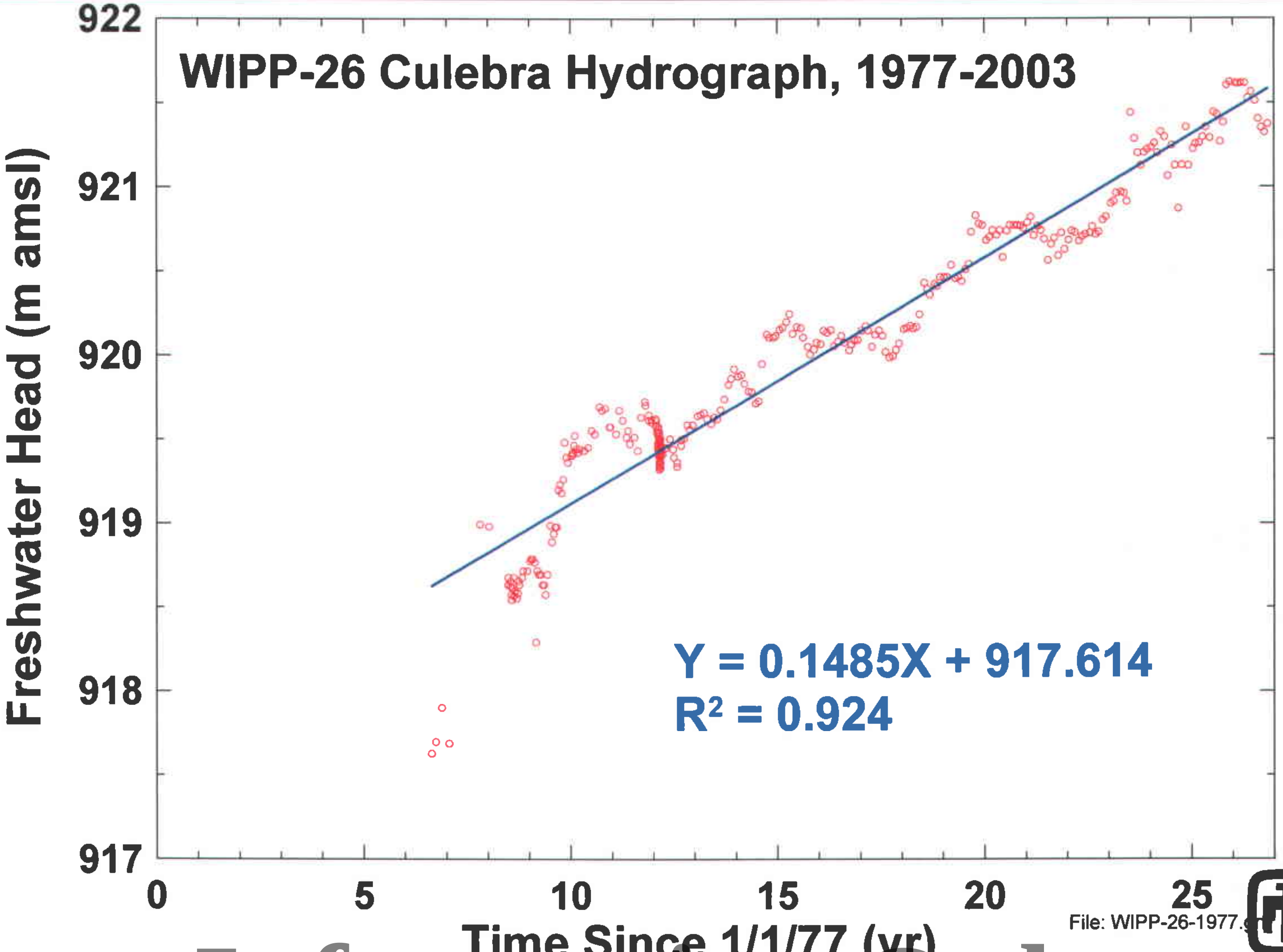
Evaluation Procedure for Anthropogenic Scenarios

- Calculate average rates of water-level rise for wells
- Collect data to quantify fluid discharge onto tailings pile
- Collect data to identify candidate leaky wells
- Model scenarios using transmissivity (T) fields developed for CRA-2004

Hydrograph Evaluation



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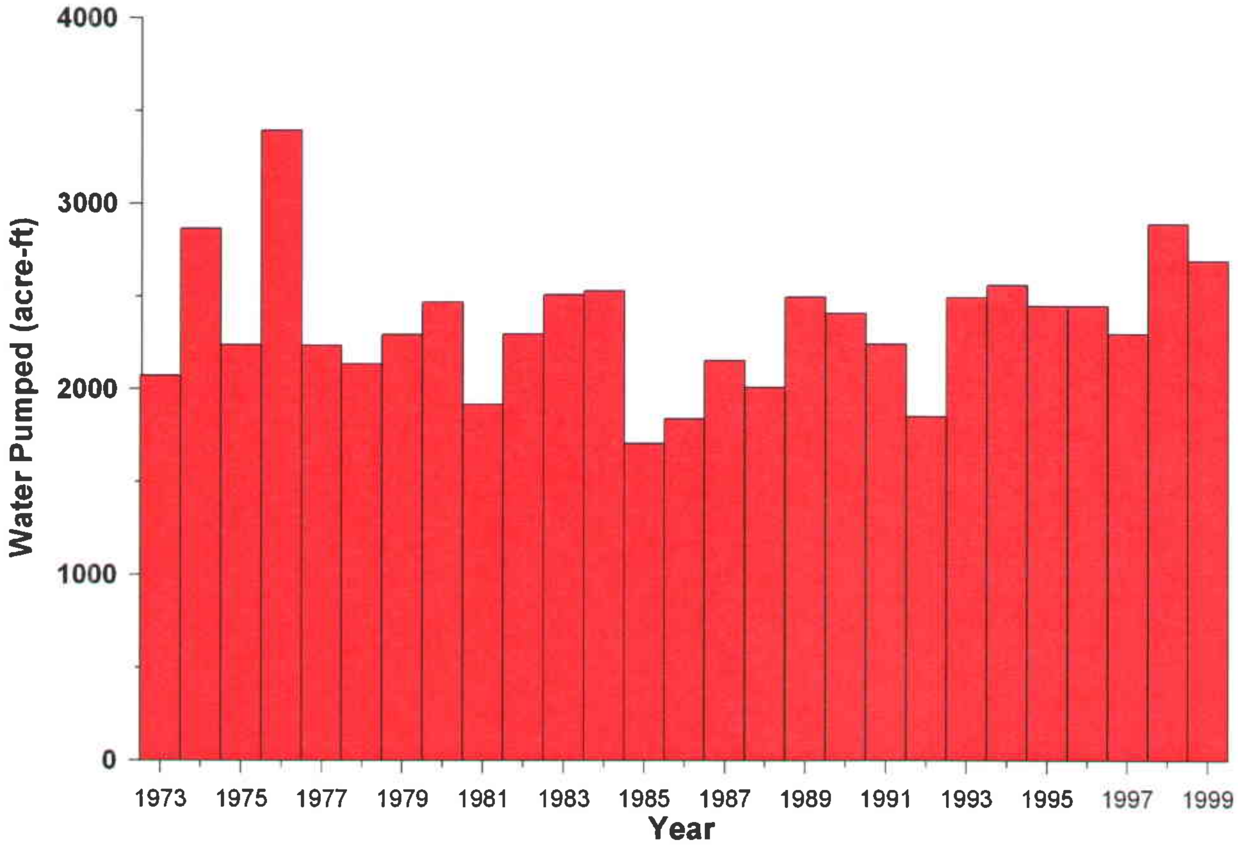
Intrepid East Water Usage Data



- Intrepid pumps ~2400 acre-ft/yr for potash processing, of which ~2200 acre-ft/yr is discharged onto their tailings pile
- 50% is thought to evaporate, and 50% infiltrates

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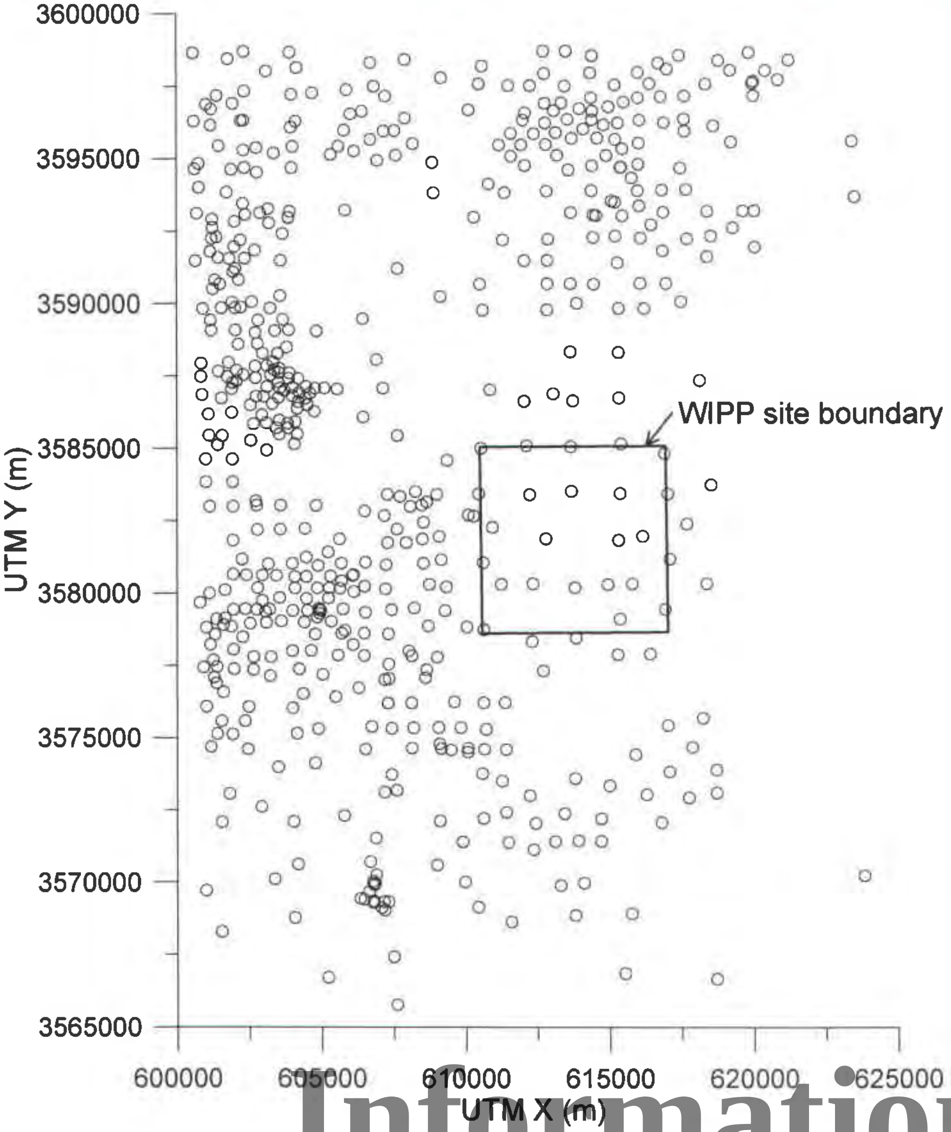
Potash Exploration Holes Around WIPP



- Potash exploration holes are plugged and abandoned right after drilling
- BLM P&A records were reviewed to evaluate efficacy of P&A

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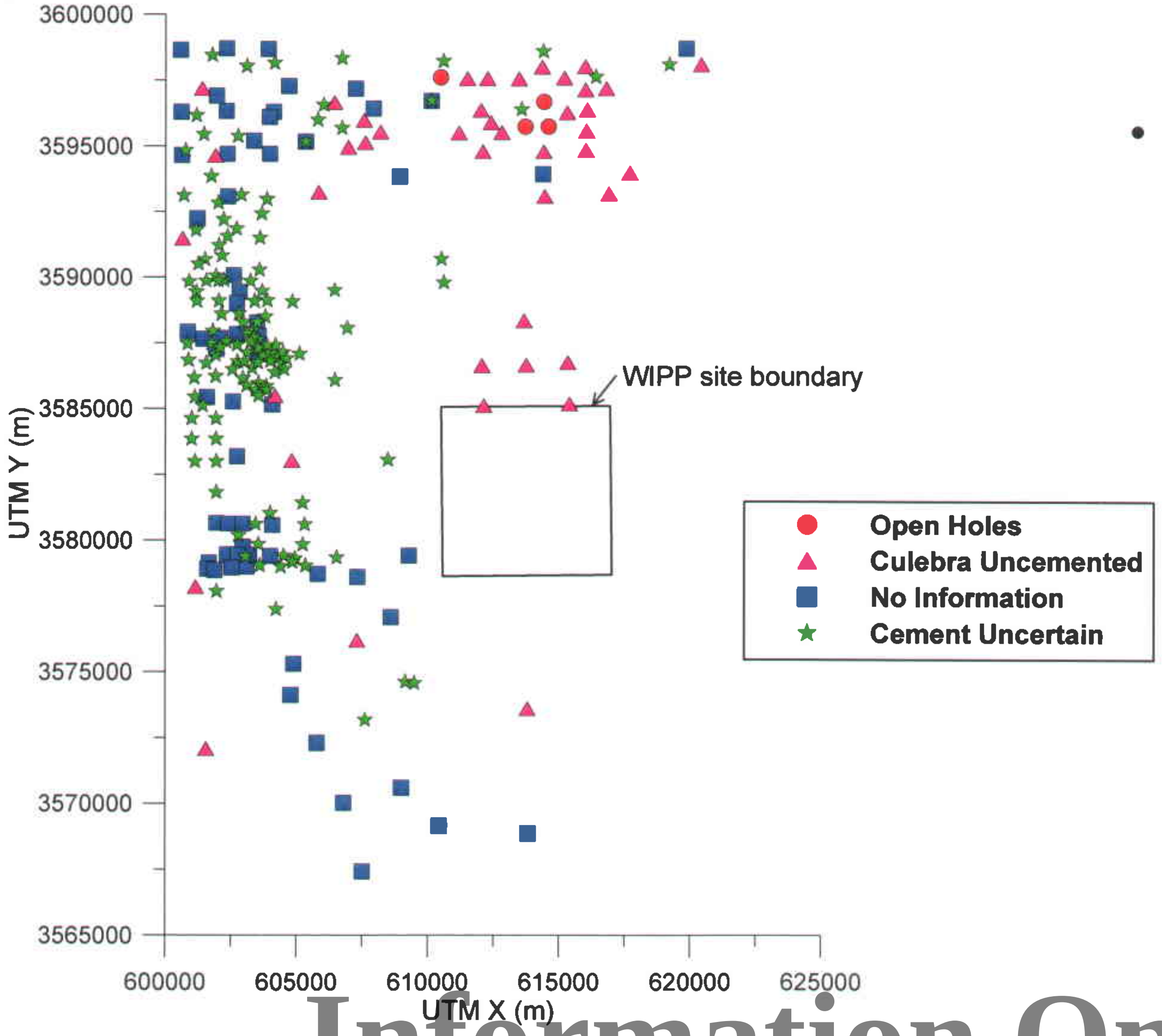
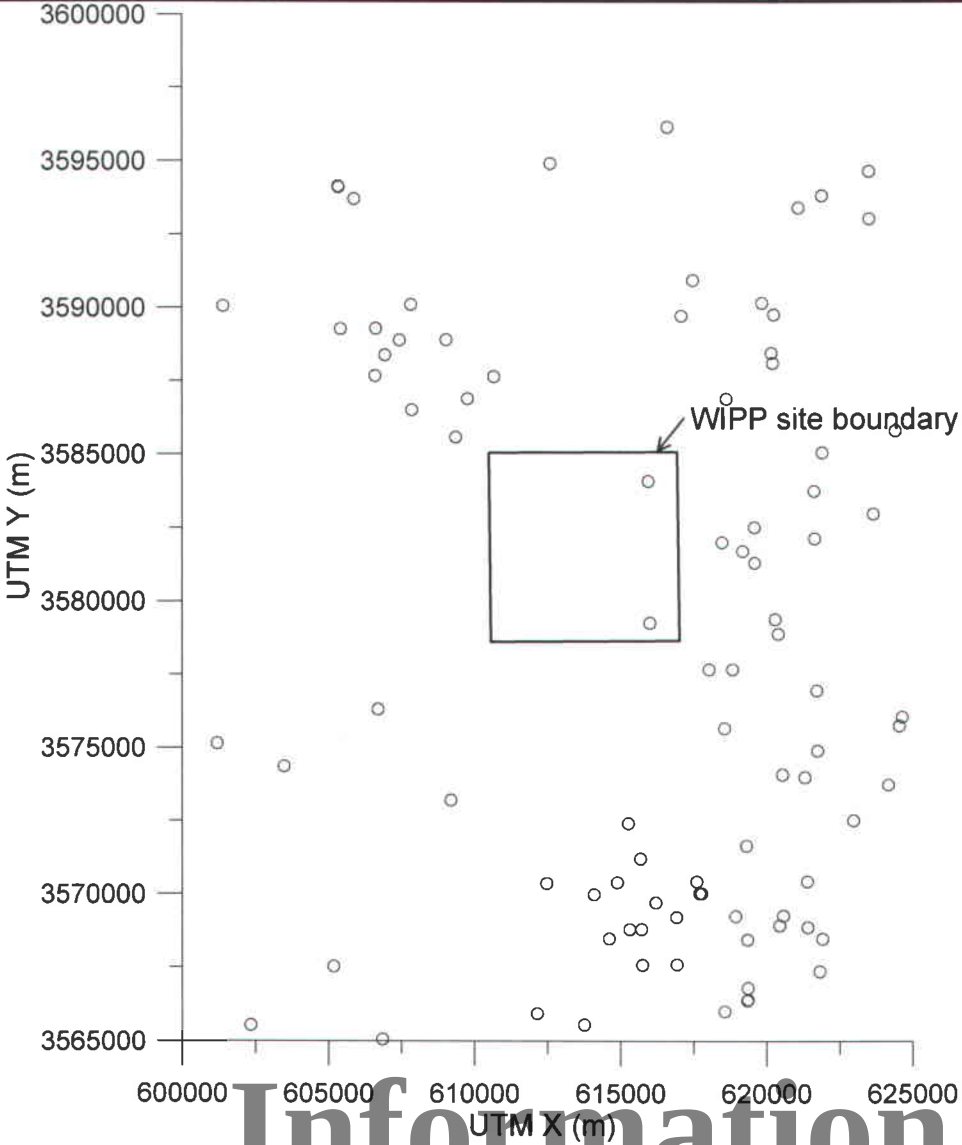
Potentially Leaking Potash Holes



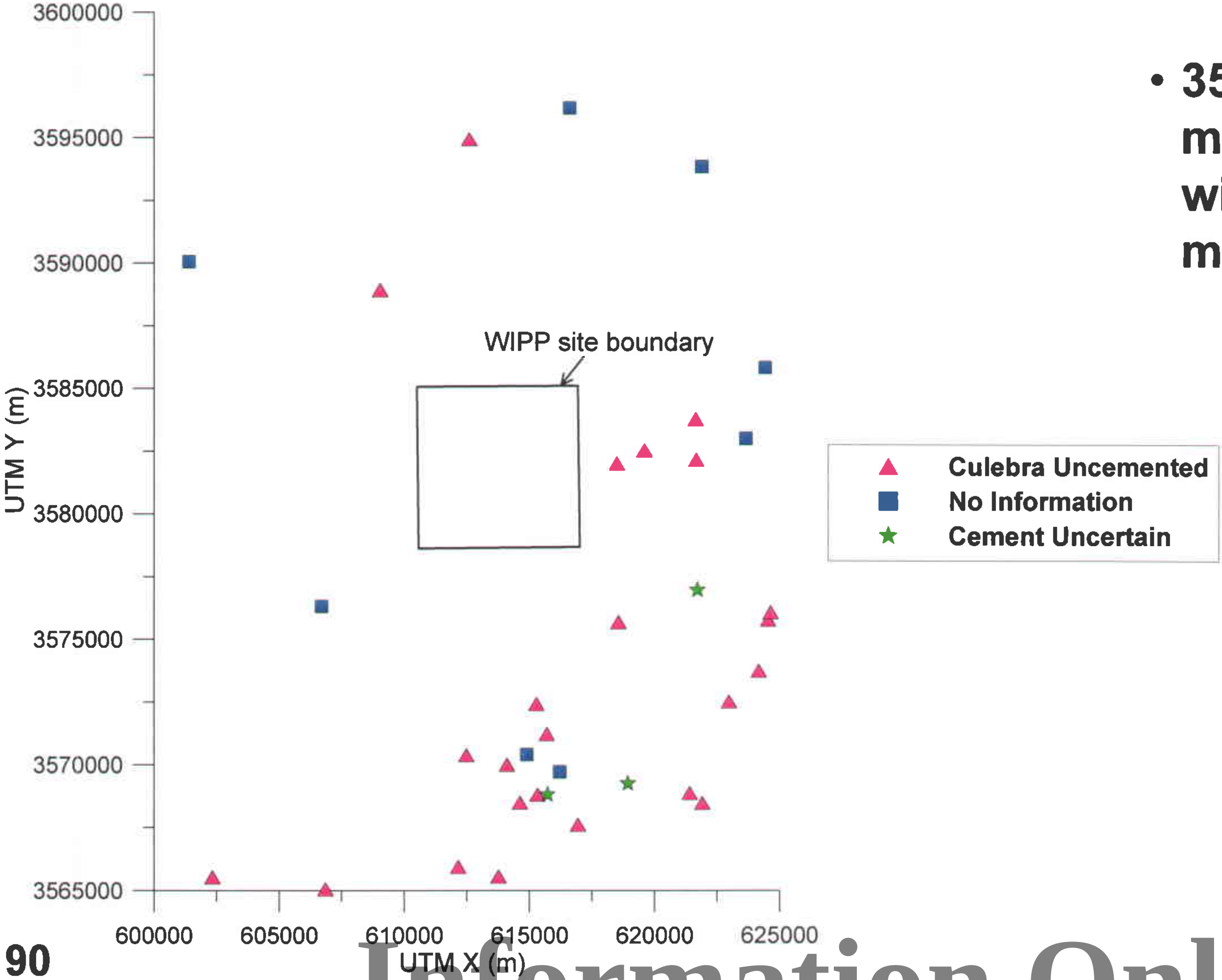
- **26 holes may be leaking within CRA-2004 modeling domain**

"Plugged" Oil and Gas Exploration Holes Around WIPP



- P&A records were reviewed to evaluate efficacy of P&A of oil and gas wells

Potentially Leaking Oil and Gas Holes



- **35 oil/gas wells may be leaking within CRA-2004 modeling domain**

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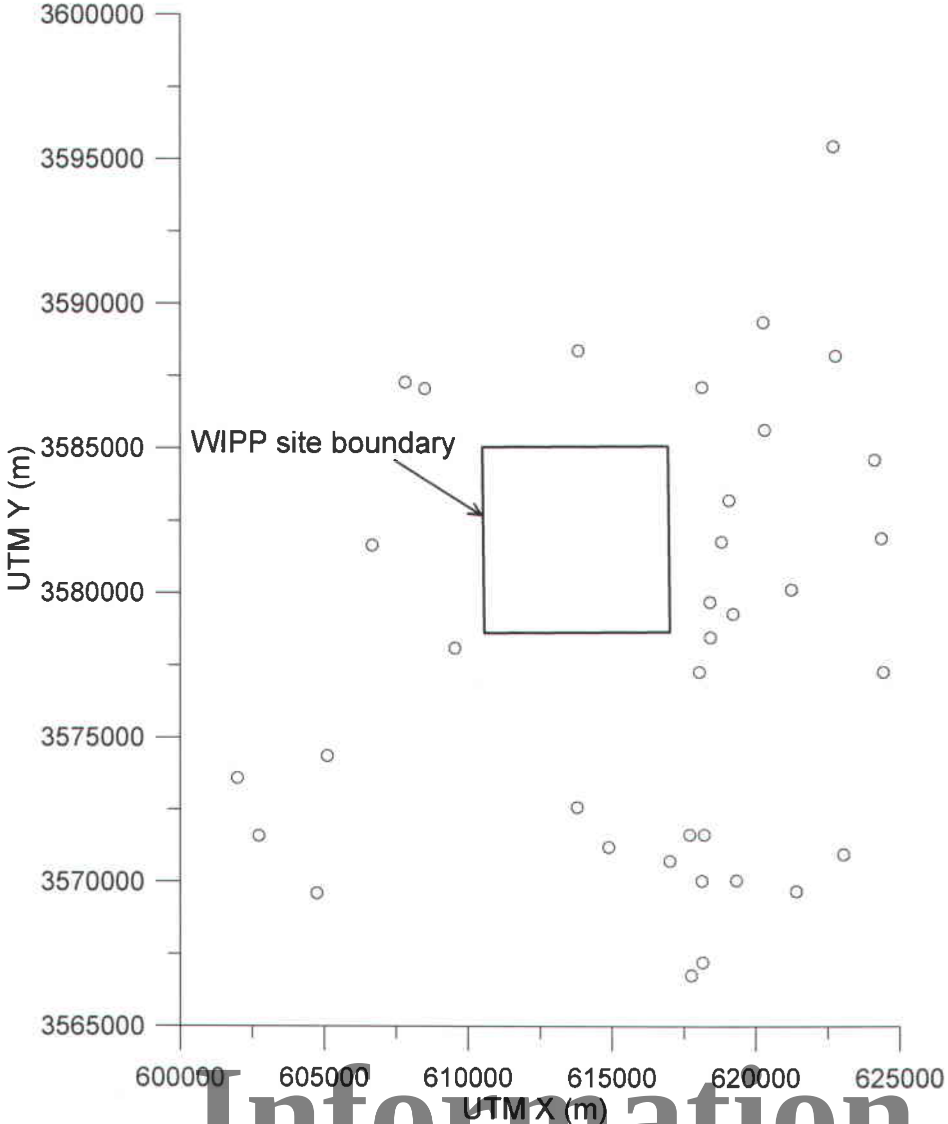
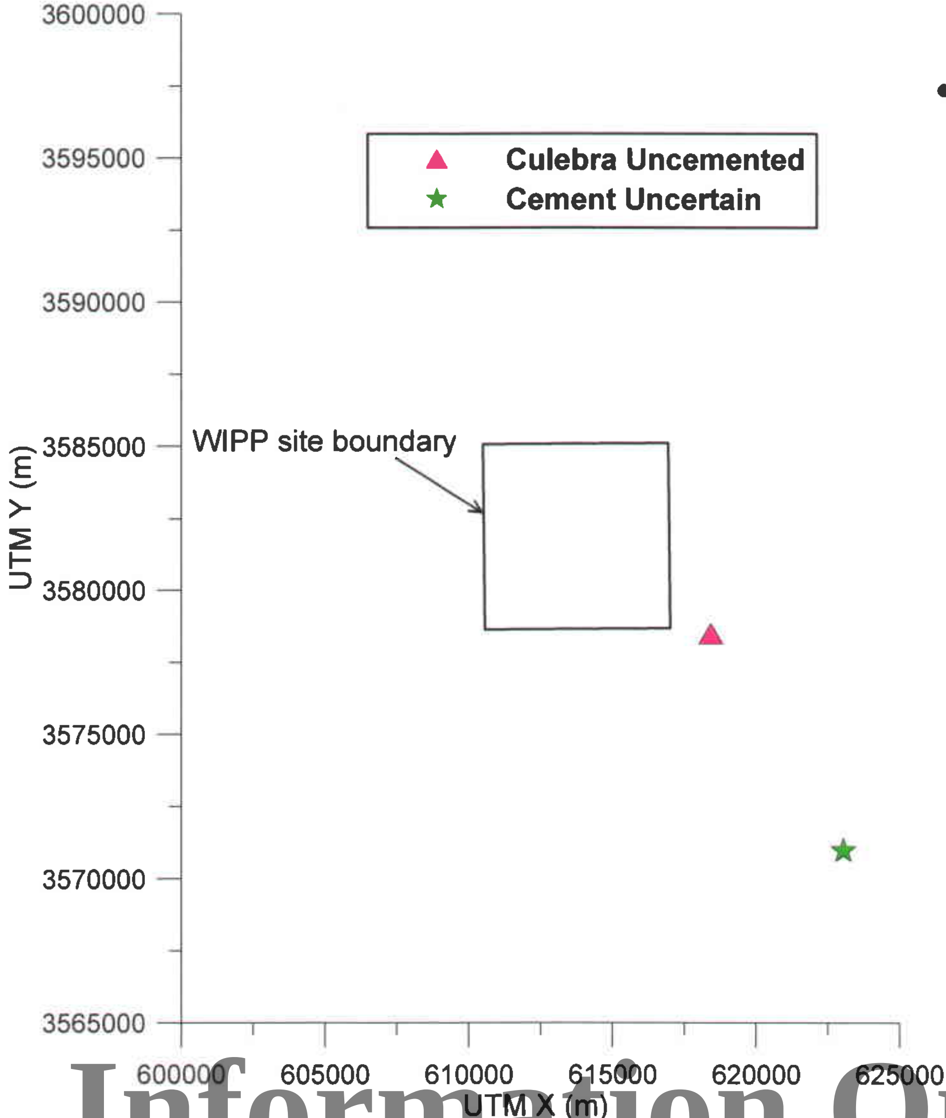
Injection/Salt Water Disposal Wells Around WIPP



- Completion records were reviewed to evaluate isolation of Culebra in salt water injection wells

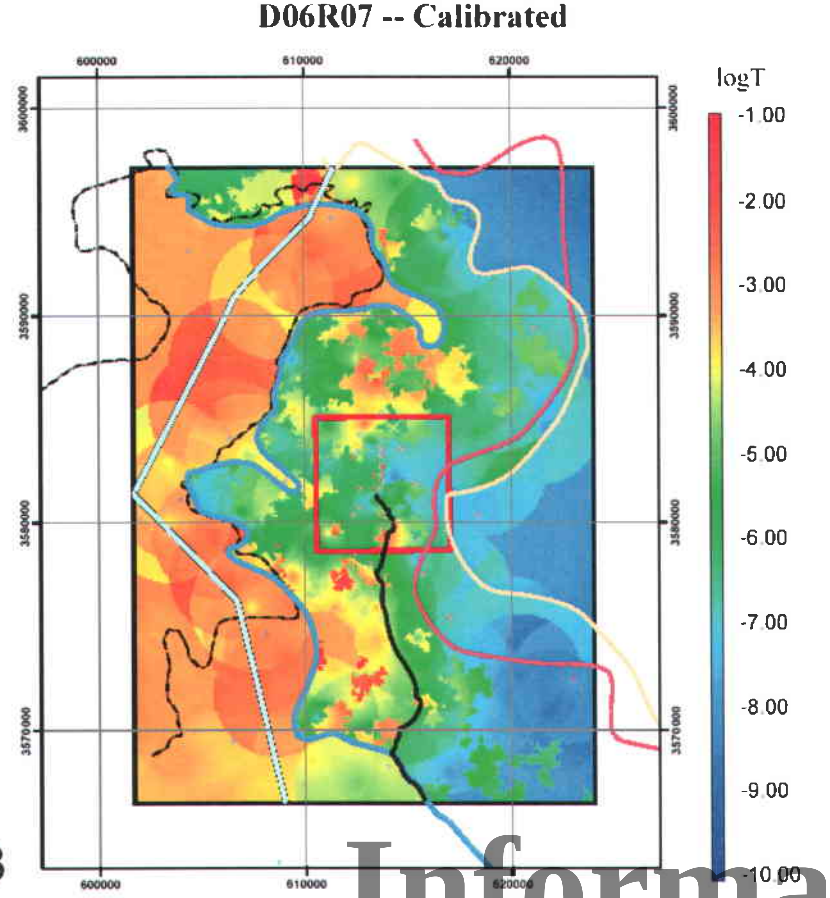
Potentially Leaking Injection/SWD Wells

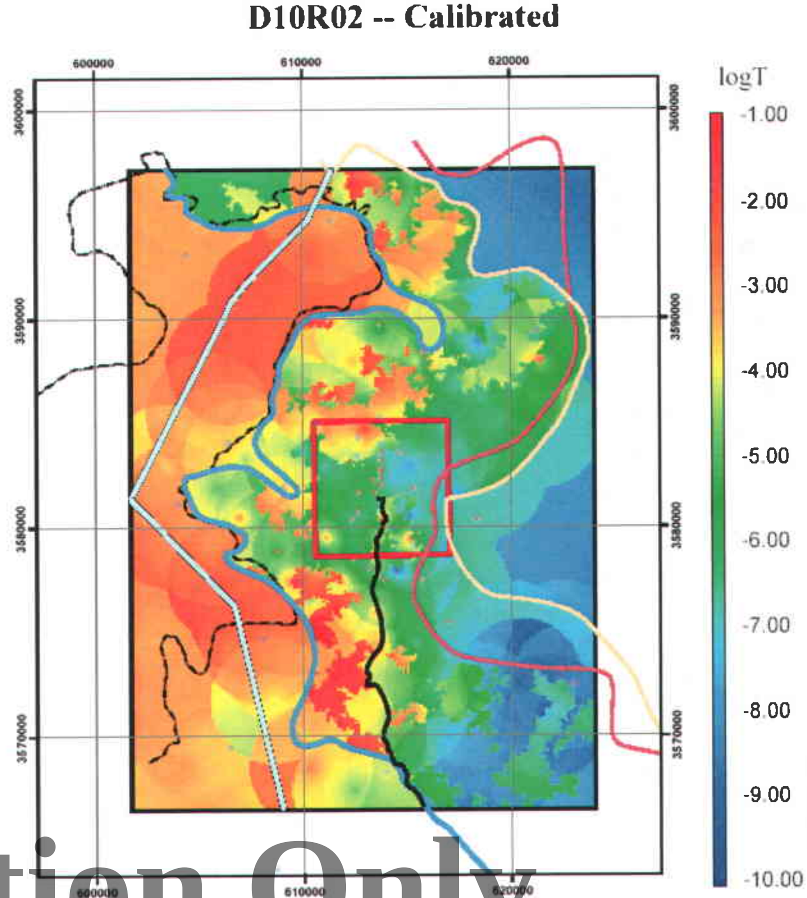


- 2 holes may be leaking within CRA-2004 modeling domain

Scenario #1 Modeling

The 100 Culebra T-fields created for CRA-2004 were used to simulate leakage into the Culebra at the Intrepid East tailings pile over a 27-year period





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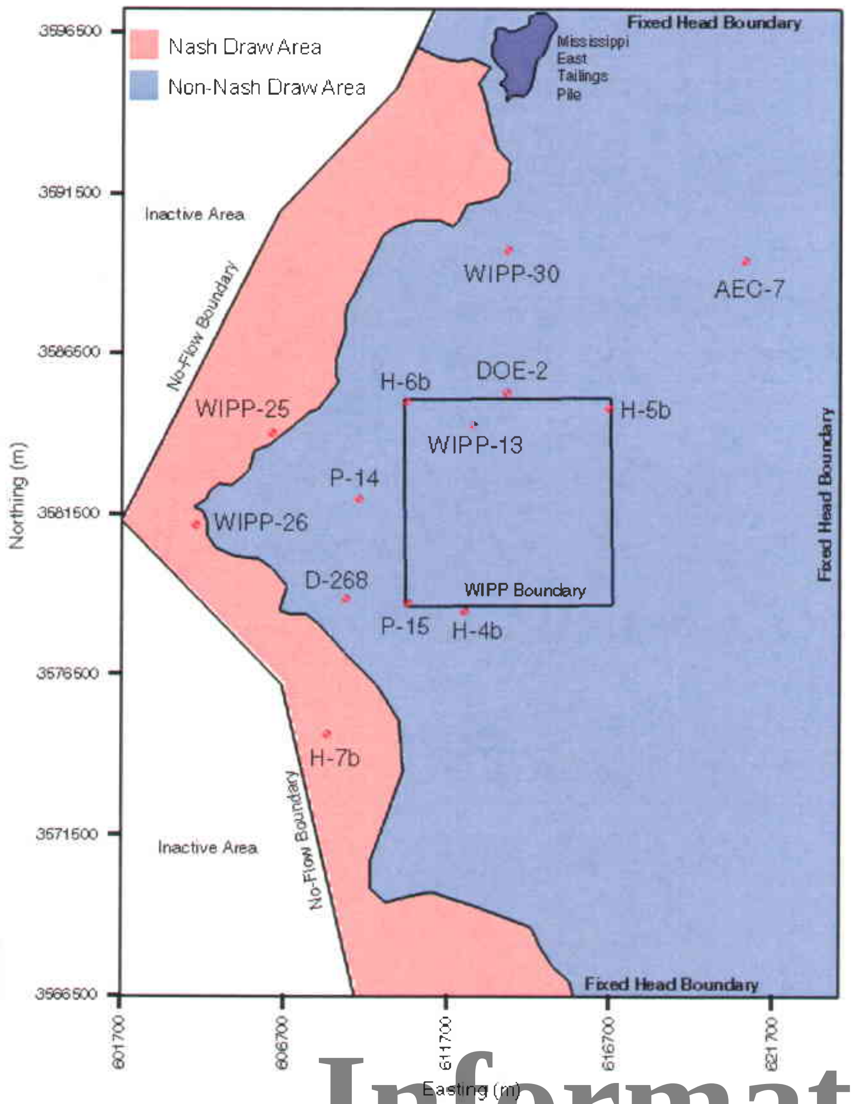
Modeling Domain for Scenario #1



- The modeling attempted to match the average rates of water-level rise at 13 wells over the last 10-15 years by adjusting storativity in Nash Draw, storativity outside of Nash Draw, and the leakage flux at the tailings pile

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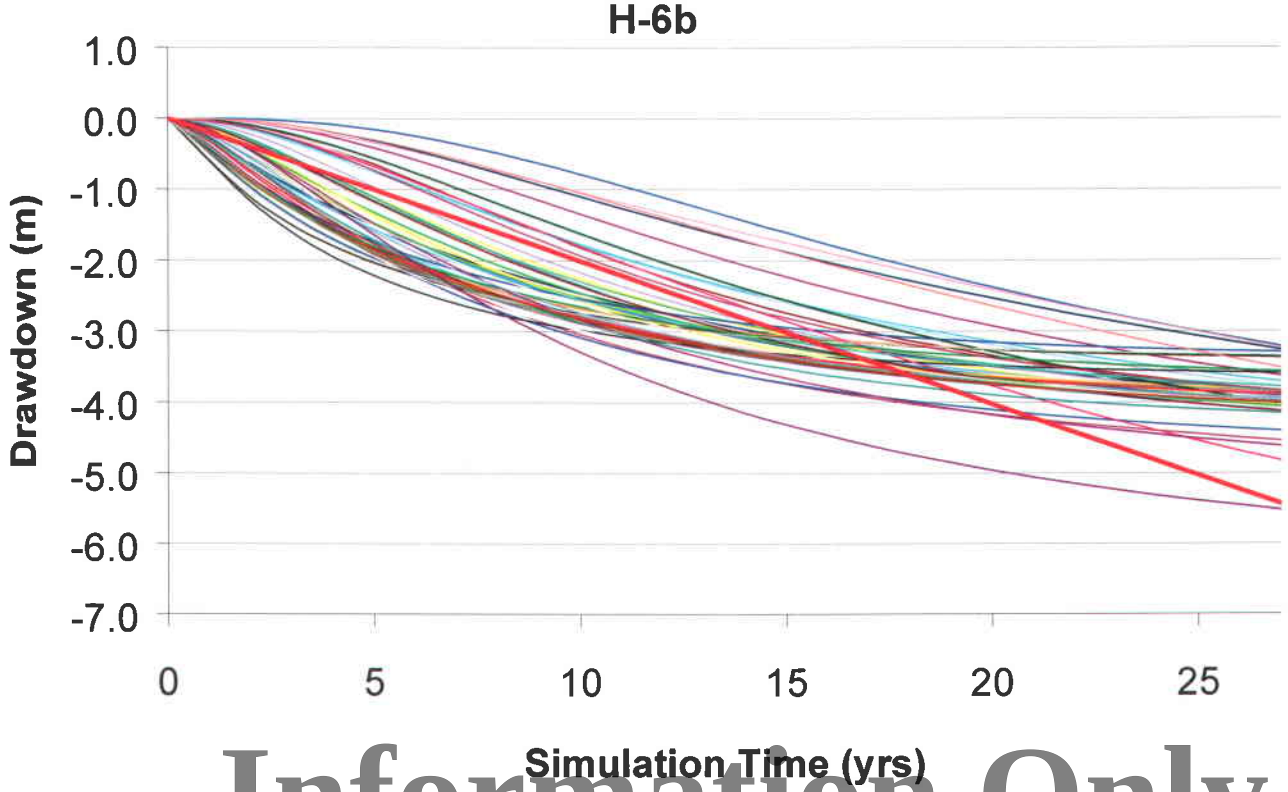
Results from Scenario #1

On average, only 7% (74 acre-ft/yr) of the brine discharged onto the tailings pile needs to reach the Culebra to cause water levels to rise by 1-5 m over the 27-yr simulation period



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Scenario #2 Modeling

- The 100 Culebra T-fields created for CRA-2004 were used to simulate leakage into the Culebra from 26 potash holes over a 15-year period
- The modeling attempted to match the average rates of water-level rise at 12 wells over the last 6 or 15 years by adjusting storativity in Nash Draw, storativity outside of Nash Draw, and the leakage flux through the holes combined into four groups by location (same flux through each hole in a group)

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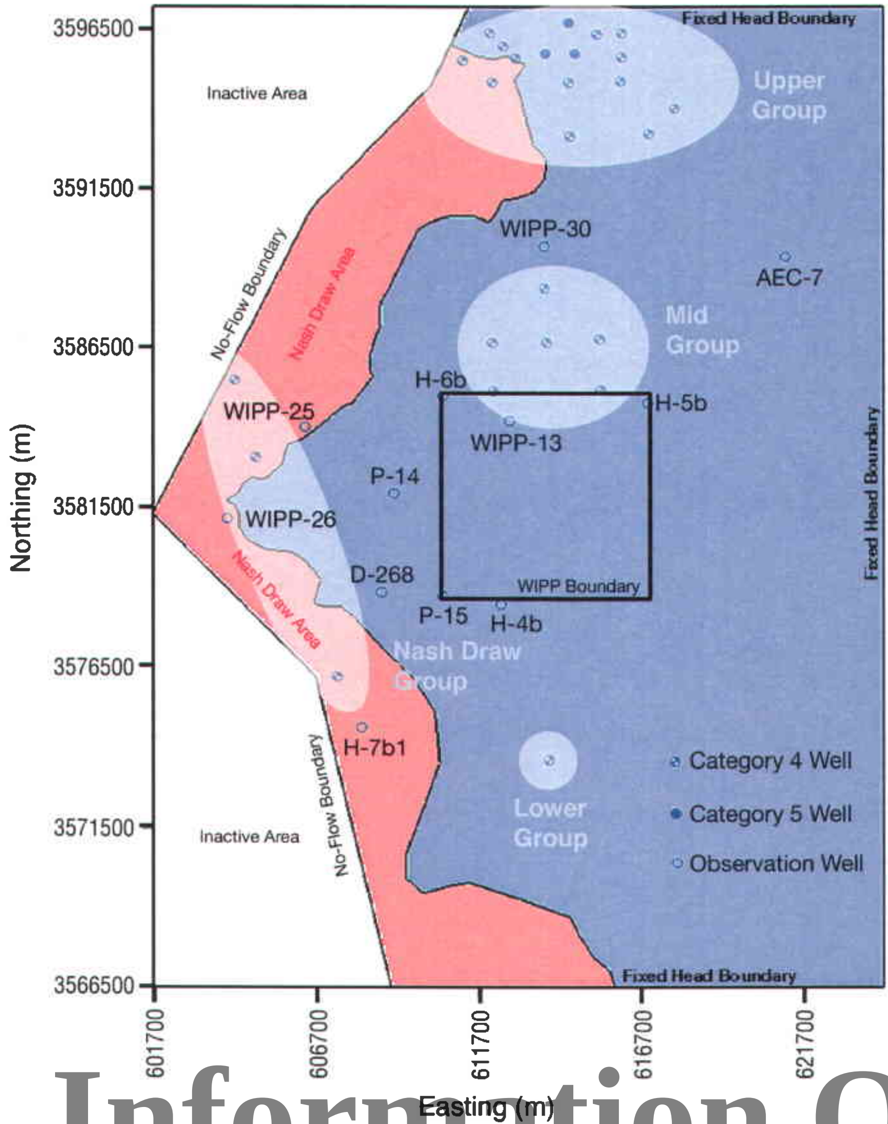
Modeling Domain for Scenario #2



26 potentially leaking holes are divided into 4 groups

Results of Scenario #2 Modeling

- On average, only 110 m^3/day (20 gpm; 33 acre-ft/yr) of brine needs to leak into the Culebra through the 26 holes to cause water levels to rise by 0.5-1.5 m over the last 6 yr of the 15-yr simulation period
- Distributed nature of source accounts for less water needed than in Scenario #1
- Wells in the mid-group are relatively unimportant with wells in the upper (essentially under the Intrepid East tailings pile) and lower groups showing the most influence on the system

Other Scenarios

- Given the physically reasonable (and small) amounts of leakage required to cause the observed rise, and the difficulty of proving a particular hole is leaking, the leakage hypothesis is accepted as plausible
- Leaking oil and gas wells and/or leaky injection wells could be contributing to the observed water-level rise
- Recharge to a shallow water table hydraulically connected to the Culebra through subsidence fractures in northern Nash Draw could also be contributing to the water-level rise
- No further modeling is planned

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Potential Impact of Anthropogenic Leakage

- Culebra water levels may be expected to continue rising for at least as long as Intrepid East operations continue, and possibly much longer
- Increase in heads does not automatically translate to increase in gradient
- The maximum gradient that could be produced by leakage would result from the Culebra head reaching ground surface at the Intrepid East tailings pile
  - If Culebra head remained unchanged at the southern WIPP boundary, the gradient would be increased ~six-fold
  - Head is also increasing south of WIPP, so the gradient increase would be less
- Flow direction would remain N-S because of bounding low T to the east

Summary of Water-Level Rise

- Three potential anthropogenic causes of changing water levels have been identified
- The observed long-term water-level rise could be caused by leakage from the Intrepid East tailings pile and/or by leakage through poorly plugged potash and/or oil and gas exploration holes
- Recharge of a shallow water table in northern Nash Draw could be contributing to the Culebra water-level rise if hydraulically connected to the Culebra by subsidence fractures or gypsum karst
- Recharge from precipitation SW of the WIPP site may be contributing to water-level rise south of WIPP

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Support for Conceptual Model Derived from Hydrologic Studies

Support for Conceptual Model Derived from Hydrologic Studies (1)

- Water flows into the WIPP site area primarily from the north and continues to the south following the path of least resistance
- The Culebra is bounded on the east by a region of extremely low transmissivities and high heads, possibly above ground surface
- Outside of Nash Draw, the Culebra is confined and does not receive modern recharge from rainfall
- Within Nash Draw, the Culebra is unconfined and responds to major rainfall events
- Head changes associated with rainfall in Nash Draw propagate through the confined Culebra

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Support for Conceptual Model Derived from Hydrologic Studies (2)

- The Culebra displays extreme variability in T (~10 orders of magnitude)
- Heterogeneity in the Culebra causes the non-radial late-time derivative responses observed
- The Culebra behaves hydraulically as a double-porosity (fractured) medium in some locations and as a single-porosity (unfractured) medium in others
- Fractured and unfractured regions can be mapped using inferred diffusivity values, showing continuity over large distances

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Support for Conceptual Model Derived from Hydrologic Studies (3)

- A northeast to southwest trending band of low T separates the high-T region in the NW WIPP site from the high-T region in the SE WIPP site
- The high-T zone in the SE part of the WIPP site continues at least 10 km to the south
- Rising water levels can plausibly be attributed to leakage from the Intrepid East tailings pile and/or through poorly plugged and abandoned holes, perhaps combined with leakage related to rainfall and/or potash effluent discharge through fractures/karst in Nash Draw