Nevada National Security Site Underground Test Area (UGTA) Flow and Transport Modeling – Approach and Example

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Outline

- Nevada National Security Site (NNSS)
- Environmental Management (EM) mission at NNSS
- *Federal Facility Agreement and Consent Order* (FFACO)
- UGTA strategy and approach
- NNSS inventory
- Example of UGTA strategy implementation at Yucca Flat
- Summary

EM Mission at NNSS

- Characterization and remediation activities at radioactive and non-radioactive contaminated sites
  - Activities focus on groundwater, soil, and onsite infrastructure contamination from historic nuclear testing
- Low-level radioactive and hazardous waste management and disposal
  - National disposal facility for the U.S. Department of Energy (DOE) Complex (Area 5 Radioactive Waste Management Site)
- Environmental planning, compliance, and monitoring

FFACO

- FFACO provides approach for DOE to develop and implement corrective actions under the regulatory authority and oversight of State of Nevada Division of Environmental Protection (NDEP)
- Agreement for governing the process to identify, characterize, and implement corrective actions at historical sites used in the development, testing, and production of nuclear weapons
- Tri-party agreement
  – NDEP, DOE, and U.S. Department of Defense

FFACO UGTA Strategy Assumptions

1. Groundwater technologies for removal or stabilization of subsurface radiological contamination are not cost-effective
2. Closure in place with monitoring and institutional controls is the only likely corrective action
3. The important potential risks from radiological contamination of groundwater are to the workers, public, and environment; and exposure to these risks requires access to groundwater

– *Nevada Test Site Environmental Management End State Vision* (DOE, 2006)

UGTA Activity Objectives

- Identify nature and extent of groundwater contamination resulting from radionuclides produced during underground nuclear weapons testing
- Model groundwater flow and contaminant transport to forecast extent of contaminated groundwater for 1,000 years into the future
- Define boundaries around each UGTA corrective action unit (CAU) to identify water that may be unsafe for domestic and municipal use

Purpose of Models in UGTA Strategy

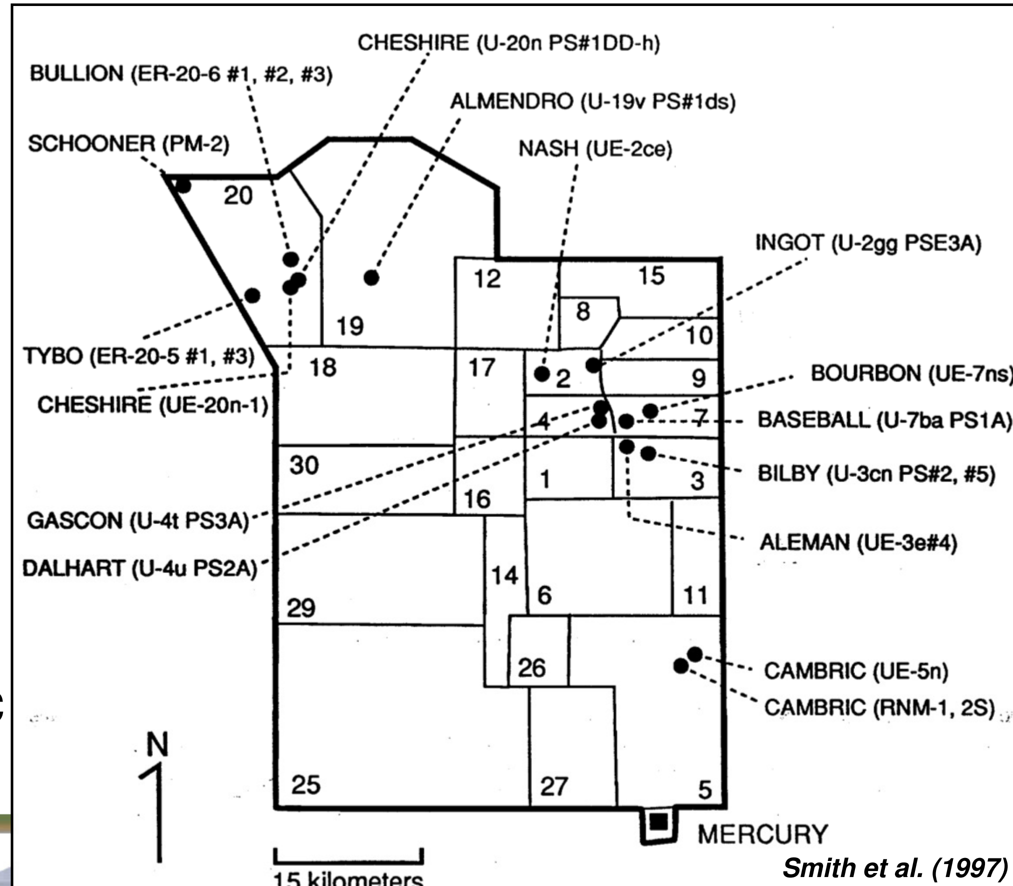
- Provide fundamental basis for identifying perimeter boundaries enclosing areas with groundwater potentially exceeding *Safe Drinking Water Act* (SDWA) maximum contaminant level (MCL)
  - Contaminant boundaries are not *predictions* of contaminant concentrations but are spatial representations of the probability of exceeding the SDWA MCL
  - Confidence developed through model evaluation and monitoring
  - Reasonable expectation that groundwater outside the contaminant boundary is less than SDWA MCL
- Significant uncertainty due to complex setting
  - Parameter and structural uncertainty
  - Produce an ensemble of contaminant boundaries
  - Uncertainty managed through institutional controls and monitoring

FFACO Regulatory Process

- Corrective Action Investigation Plan (CAIP)
  - Drilling
  - Well development/testing and sampling
  - Data analysis and evaluation
  - Modeling
- Hydrologic Data Document
- Transport Parameter Data Document
- Hydrostratigraphic Framework Model
- Hydrologic Source Term Model
- Groundwater Flow and Transport Model
- Peer Review
- Corrective Action Decision Document/Correction Action Plan (CADD/CAP)
- Model Evaluation Report
- Closure Report

NNSS Radionuclide Migration Programs

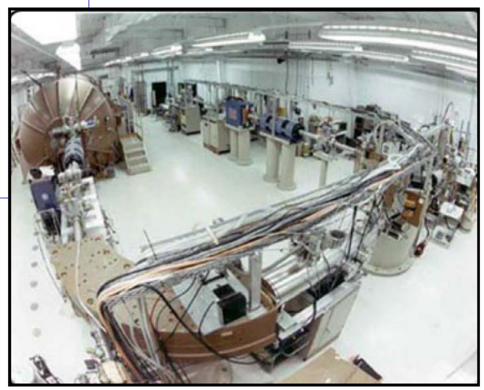
- Post-test and downgradient well sampling
- Radionuclide migration studies
  - CAMBRIC, CHESHIRE, BILBY, NASH, BOURBON
- Special studies
  - Melt glass, actinides, tritium, chlorine-36, sorption, colloids, prompt injection, overpressured areas, recharge
- Other radionuclide migration programs (International Atomic Energy Agency)



Smith et al. (1997)

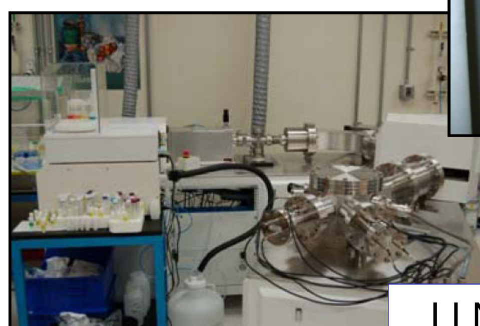
State-of-the-Art Analytical Technologies

LLNL Center for Accelerator Mass Spectrometry
- ^{14}C (~10^{-2} pCi/L)
- ^{36}Cl (~10^{-6} pCi/L)
- ^{129}I (~10^{-7} pCi/L)



LANL Gamma Counting
- ^{26}Al, ^{94}Nb, ^{126}Sn, ^{137}Cs, ^{150}Eu, ^{152}Eu, ^{154}Eu, and ^{166m}Ho (0.1–1 pCi/L)

LANL Beta Counting
- ^{85}Kr (~0.1–0.5 pCi/L)

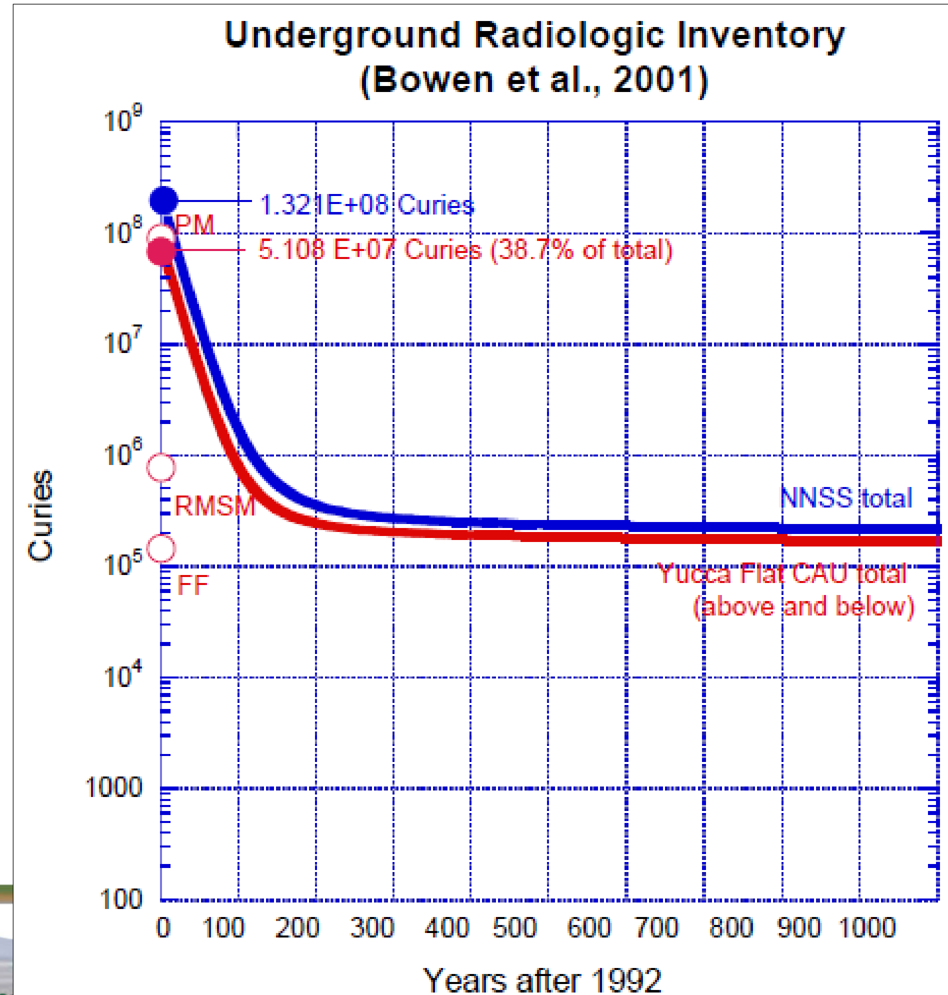


LLNL Noble Gas Mass Spectrometry
- ^{3}H (~1 pCi/L)

LLNL Inductively Coupled Mass Spectrometry
- ^{99}Tc (~10^{-4} pCi/L)
- Pu (10^{-3} pCi/L)
- U (~0.25 ng/L)

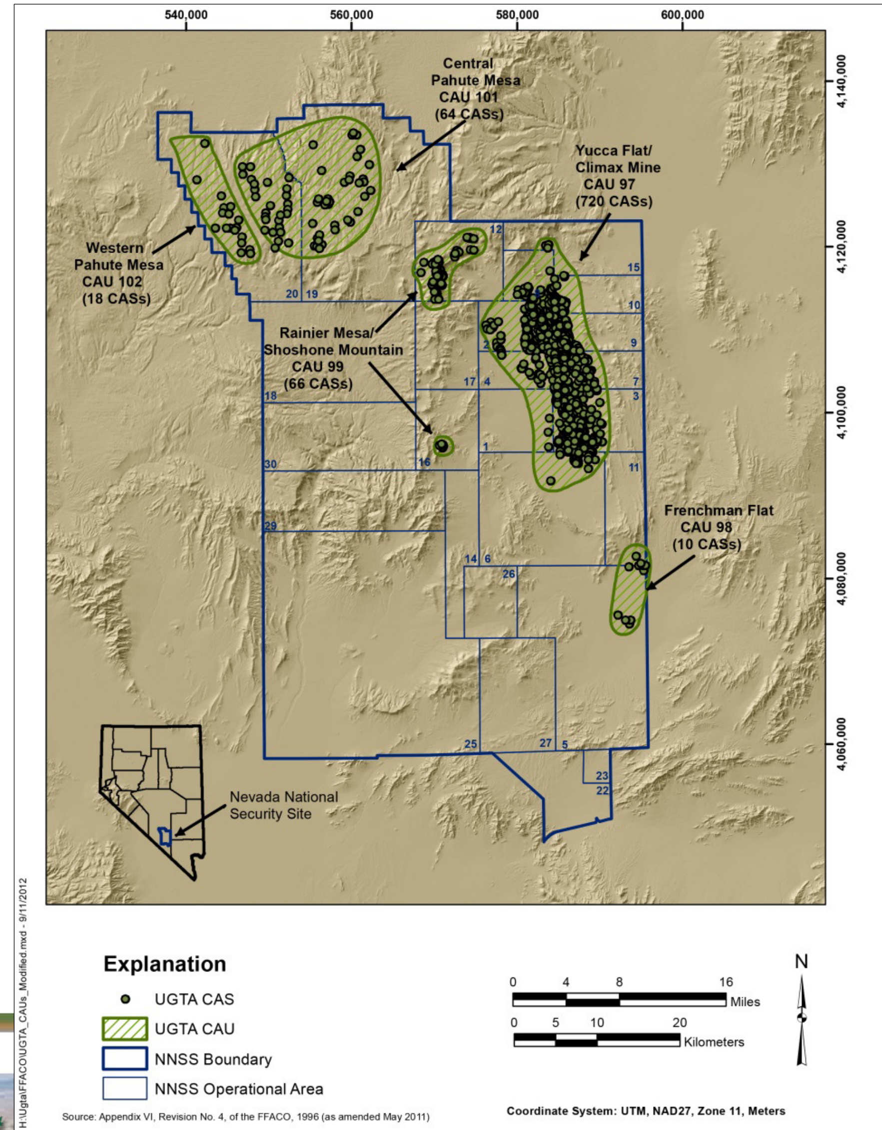
Underground Radiologic Inventory
(Includes 43 Long-Lived Isotopes)

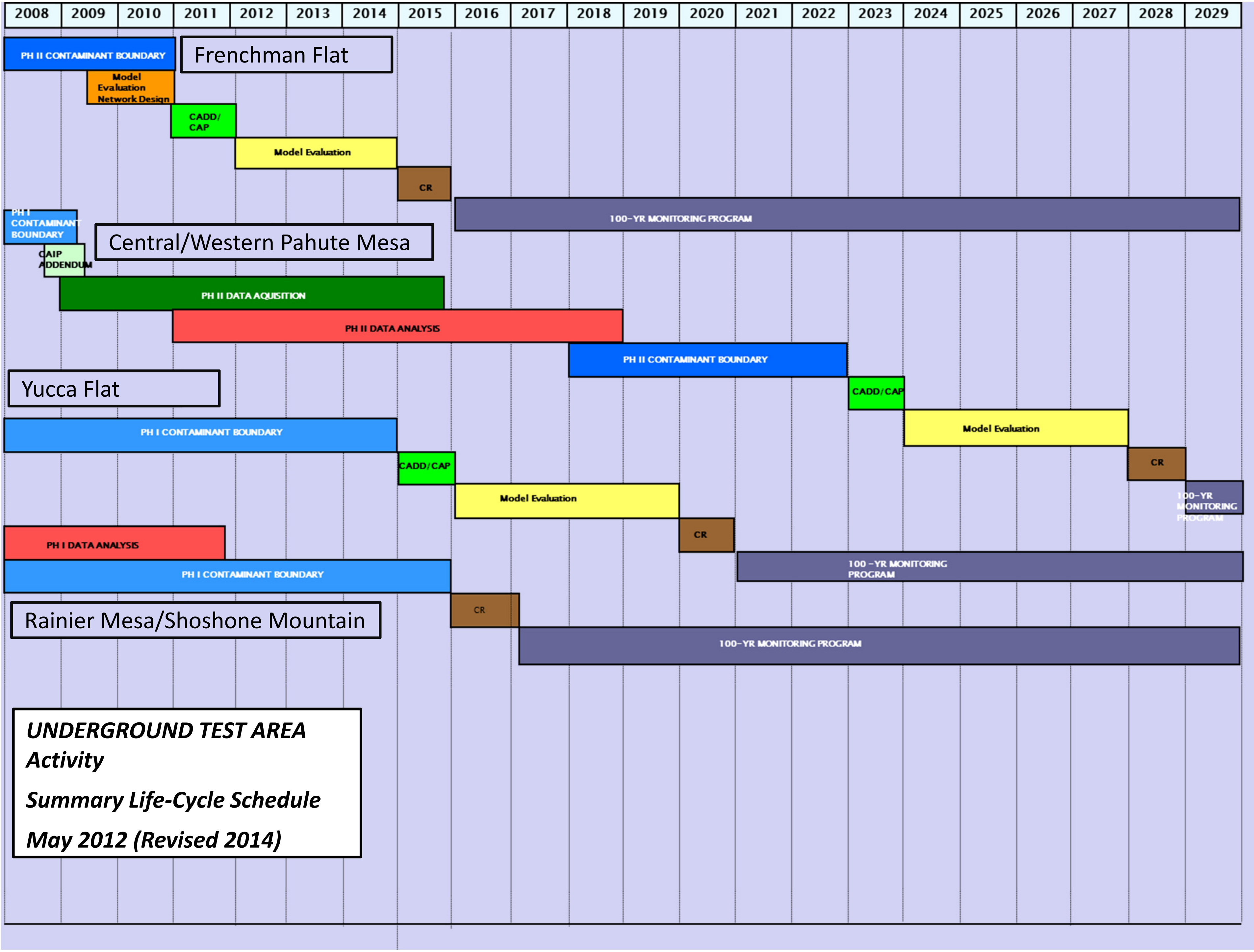
- Derived from residual fuel, fission, and activation products
  - Identified from design and drill-back diagnostic data
  - Others radionuclides generated, but half-lives too short to be of concern or of insignificant quantity
  - Includes natural contributions of potassium-40, thorium-232, and uranium-234, -235, -238



UGTA CAUs

- CAU 97: Yucca Flat/Climax Mine – 747 detonations
- CAU 98: Frenchman Flat – 10 detonations
- CAU 99: Rainier Mesa/Shoshone Mountain – 68 detonations
- CAU 101: Central Pahute Mesa – 64 detonations
- CAU 102: Western Pahute Mesa – 18 detonations




2008
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2019
2020
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2022
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2026
2027
2028
2029
Frenchman Flat
PH II CONTAMINANT BOUNDARY
Model Evaluation Network Design
CADD/ CAP
Model Evaluation
CR
100-YR MONITORING PROGRAM
Central/Western Pahute Mesa
PH I CONTAMINANT BOUNDARY
CAIP ADDENDUM
PH II DATA AQUISITION
PH II DATA ANALYSIS
PH II CONTAMINANT BOUNDARY
CADD/CAP
Model Evaluation
CR
100-YR MONITORING PROGRAM
Yucca Flat
PH I CONTAMINANT BOUNDARY
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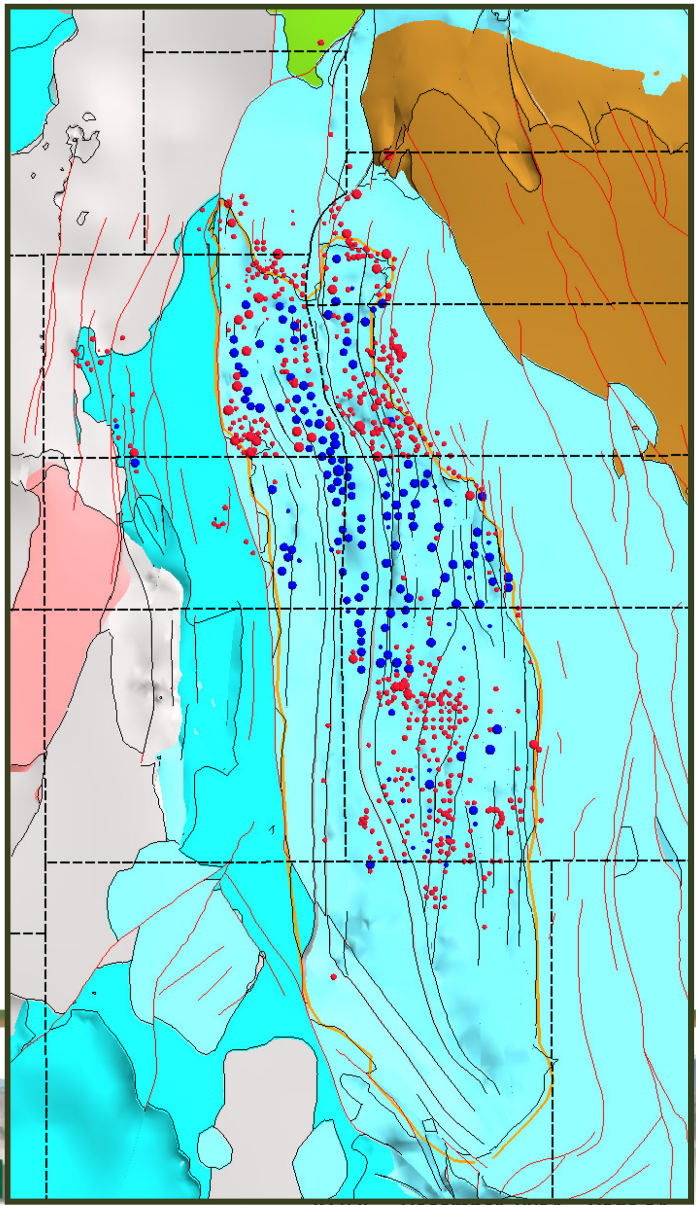
CR
100 -YR MONITORING PROGRAM
PH I DATA ANALYSIS
PH I CONTAMINANT BOUNDARY
Rainier Mesa/Shoshone Mountain
CR
100-YR MONITORING PROGRAM
UNDERGROUND TEST AREA Activity
Summary Life-Cycle Schedule
May 2012 (Revised 2014)

Yucca Flat Status

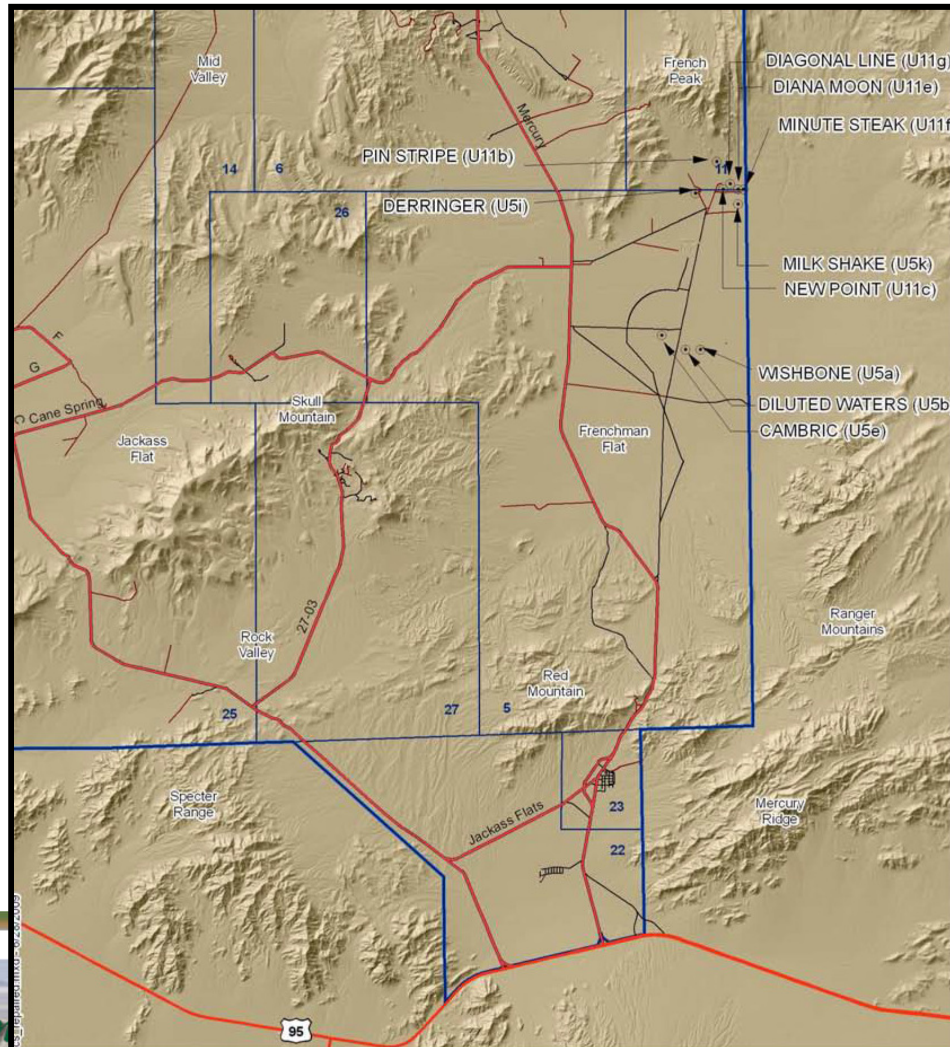
- 747 detonations (~39% of NNSS inventory)
- Phase I CAIP: 1999
- Phase I Data Collection: 2000-2008
- Phase I Model: 2008-2013
- Phase I Peer Review: 2014
- CADD/CAP: 2015



- Circles represent 2x cavity radius. Blue circles have working points below water table. Red circles have working points above water table.
- Cavity radius is calculated using the maximum of the announced yield range in DOE/NV--209 (2000) and the equation in Pawloski (1999).

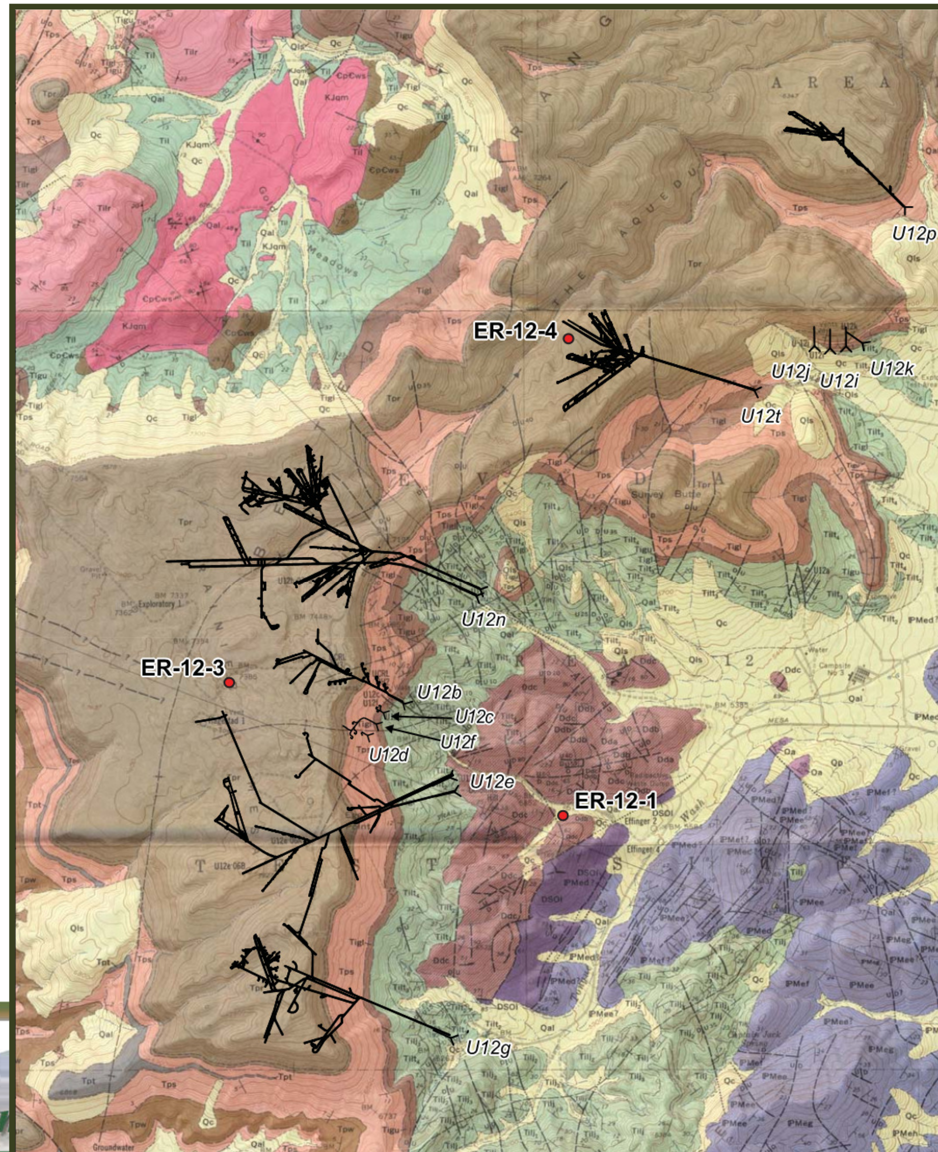
Frenchman Flat Status

- 10 detonations (~0.1% of NNSS inventory)
- Phase I Peer Review: 1999
- Phase II CAIP: 2001
- Phase II Data Collection: 2001-2007
- Phase II Model: 2007-2010
- Phase II Peer Review: 2010
- CADD/CAP: 2011
- CADD/CAP Data Collection: 2011-2012
- Model Evaluation: 2013-2014
- Closure Report: 2015



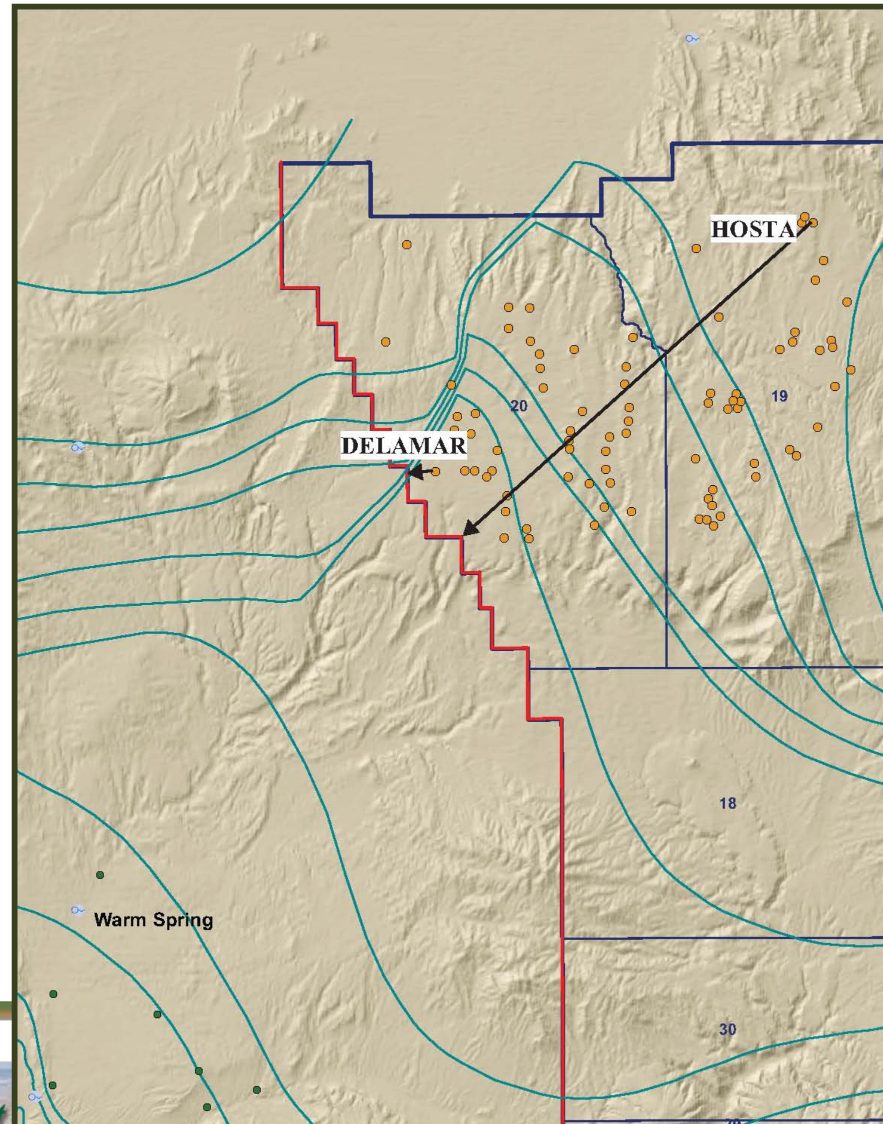
Rainier Mesa/Shoshone Mountain Status

- 68 detonations (~0.6% of NNSS inventory)
- Phase I CAIP: 2004
- Phase I Data Collection: 2004-2008
- Phase I Model: 2009-2013
- Internal Review: 2013 - 2014
- Phase I Peer Review: 2016

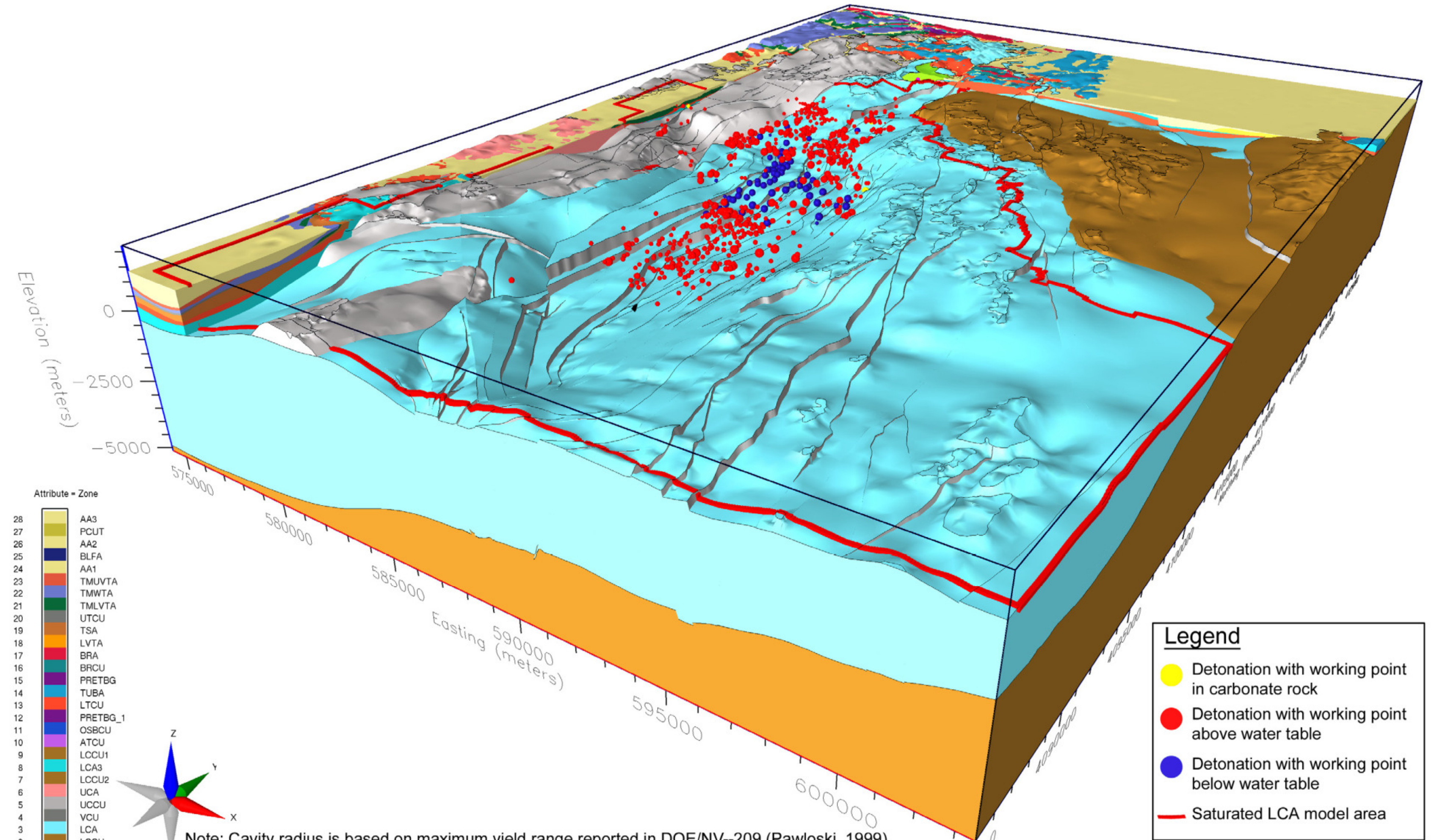


Central/Western Pahute Mesa Status

- 82 detonations (~60% of NNSS inventory)
- Phase I CAIP: 1999
- Phase I Data Collection: 2000-2008
- Phase I Model: 2005-2009
- Phase II CAIP: 2009
- Phase II Data Collection: 2010-2014
- Phase II Data Analysis: 2013-2016
- Phase II Model: 2017-2018



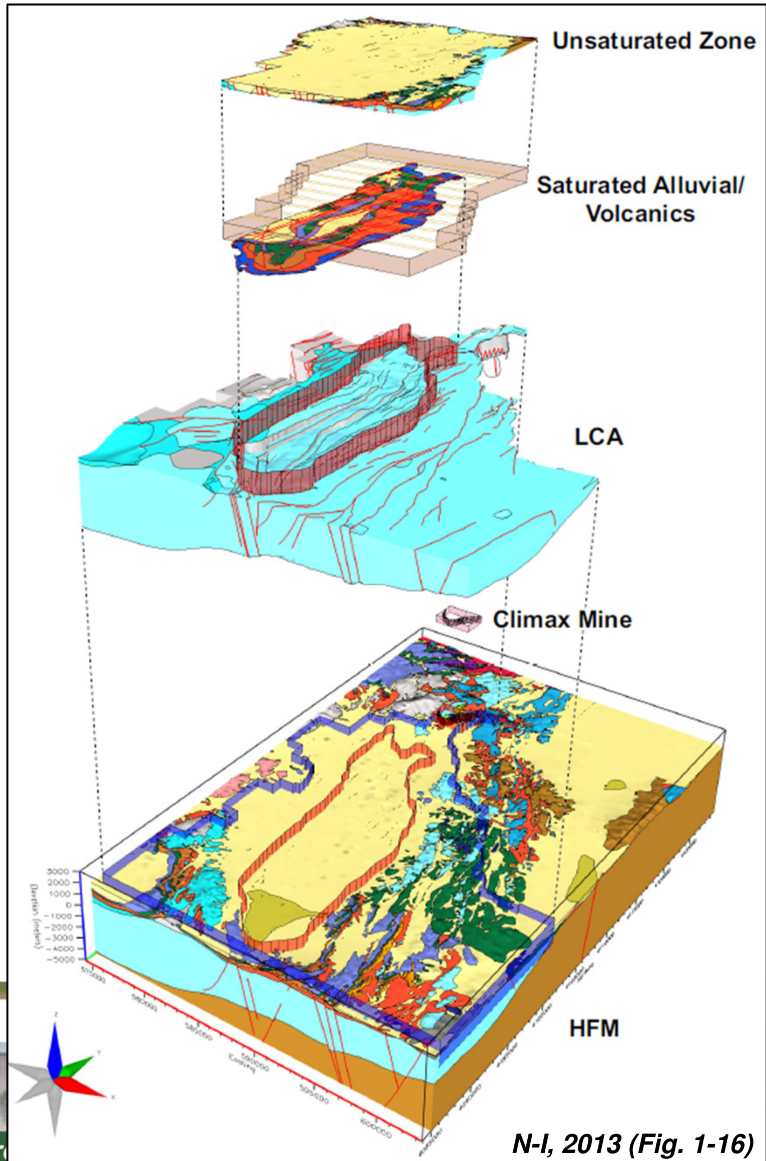
Example Application of Modeling – Yucca Flat/Climax Mine



Note: Cavity radius is based on maximum yield range reported in DOE/NV--209 (Pawloski, 1999).
Positive Y is North; Positive X is East.

Modeling Approach

- Yucca Flat model (four components for different flow and transport processes and computational efficiency)
  - Climax Mine: three (3) detonations
  - Unsaturated zone (UZ): 664 detonations
  - Saturated zone (SZ) alluvial/volcanic: 76 detonations
  - Lower carbonate aquifer (LCA): four (4) detonations
- Consistent Hydrostratigraphic Framework Model (HFM), infiltration, hydraulic properties, and source term models
- Models linked (common boundaries and water and contaminant flux)
- Forecast LCA contaminant boundary (probability of SDWA MCL exceedance)

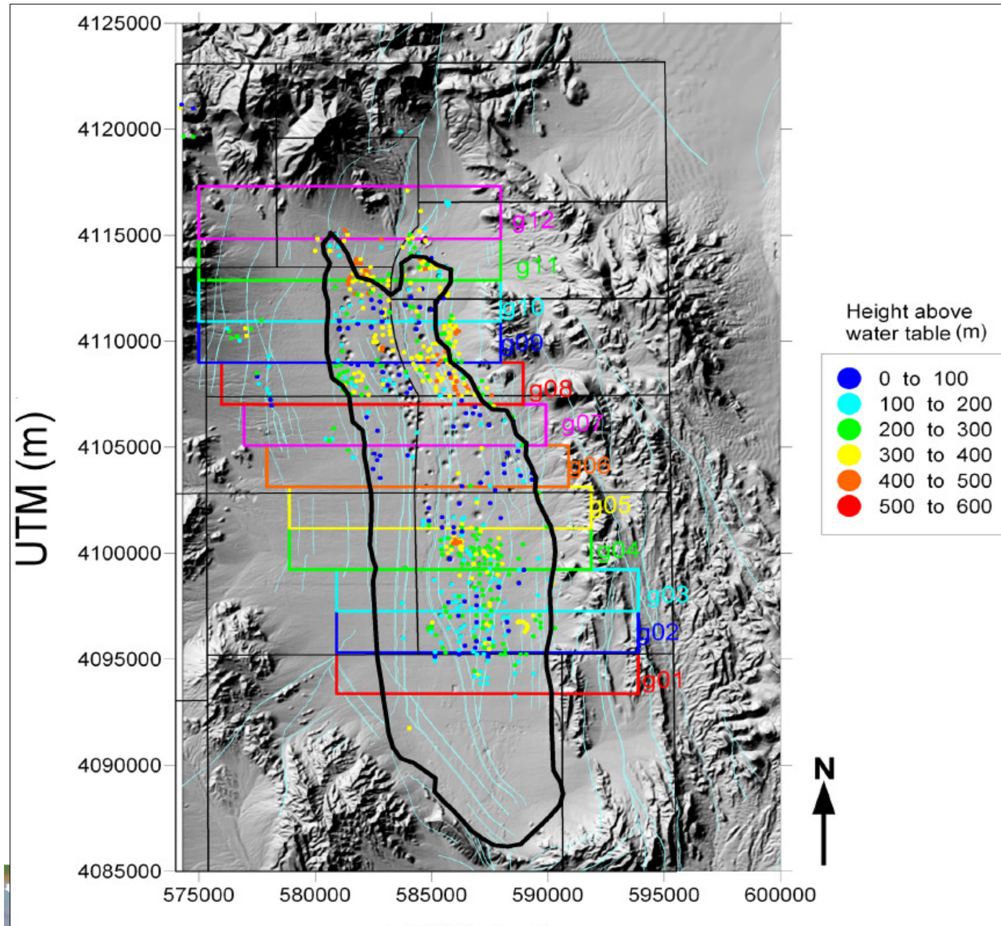


N-I, 2013 (Fig. 1-16)

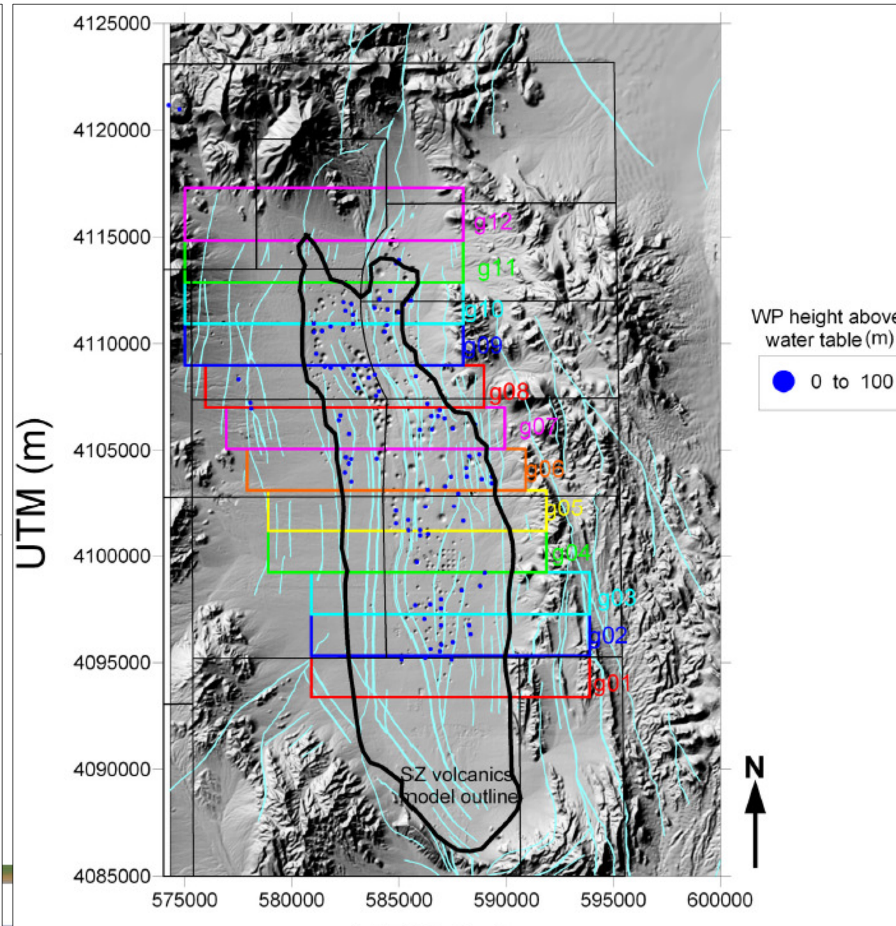
Calculation Steps To Forecast the Contaminant Boundary

1. Allocate initial activity to UZ, SZ or LCA models and distribute initial activity in exchange volumes around detonation cavities
2. Calculate UZ flow and transport to underlying SZ and LCA models
3. Calibrate SZ flow model using observed heads and transient responses
4. Calculate SZ transport to LCA model
5. Calibrate LCA flow field using observed heads and transient responses
6. Calculate advective/dispersive particle trajectories/transport times in LCA from source locations
7. Calculate LCA transport for prescribed sources and contaminant fluxes
8. Repeat step 7 for range of flow and transport parameter uncertainty
9. Calculate probability of model cells exceeding SDWA MCL concentration
10. Repeat steps 7 to 9 for alternative conceptual models and assumptions

Distribution of Underground Nuclear Tests Above the Water Table



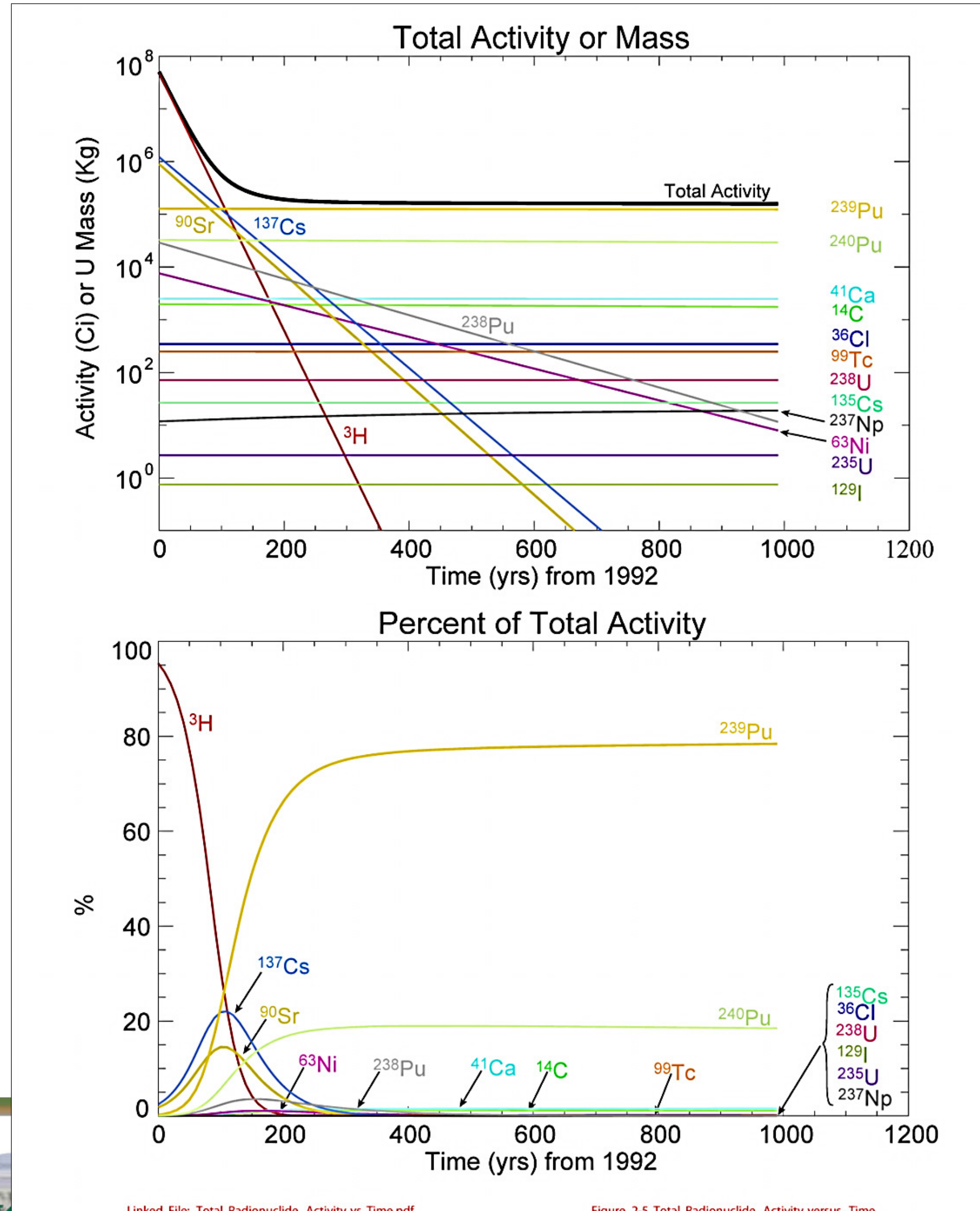
N-I, 2013 (Fig. 3-2a)



N-I, 2013 (Fig. 3-2b)

Yucca Flat Important Radionuclides

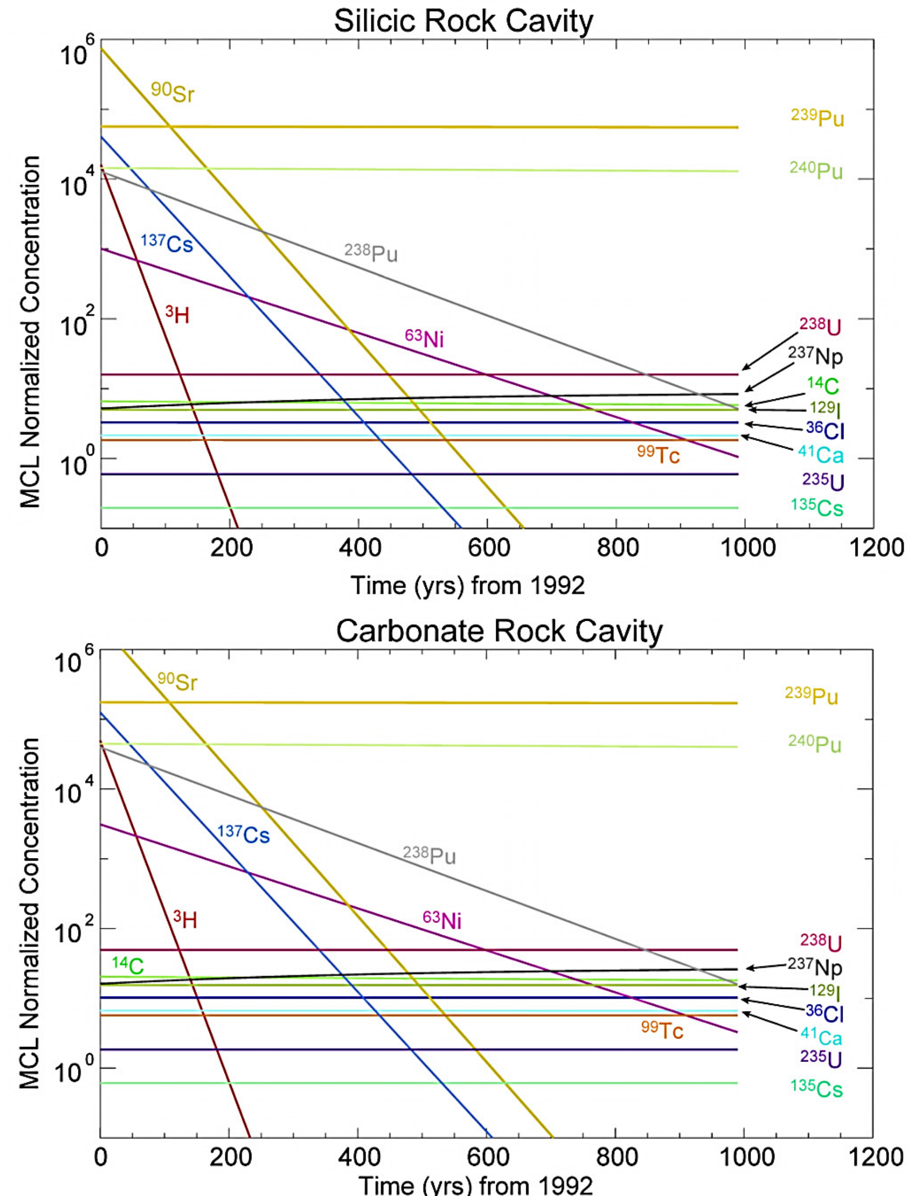
- Total activity through time
  - Radionuclides that initially dominate inventory are tritium, cesium-137 and strontium-90
- After 200 years, the dominant radionuclides are plutonium-239 and -240



N-I, 2013 (Fig. 2-5)

Yucca Flat Important Radionuclides
(continued)

- MCL normalized cavity concentration without sorption
  - Strontium-90 is 10^6 x MCL
  - Tritium is 10^4 x MCL
- Assumed values
  - Depth of Burial (*DOB*) = 400m
  - $\rho_b = 2.0$ g/cc
  - $\theta_s = 0.4$
  - Y = Yield (kt)
  - $R_c = 70.2 Y^{1/3} / (\rho_b \, DOB)^{1/4}$
  - No sorption
- Carbonate rock detonations have smaller cavity ($R_c = 9.05 Y^{1/3}$)



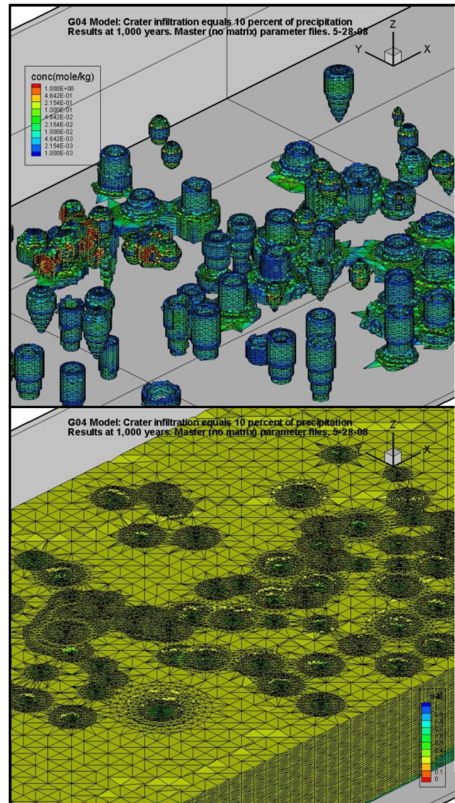
N-I, 2013 (Fig. 2-6)

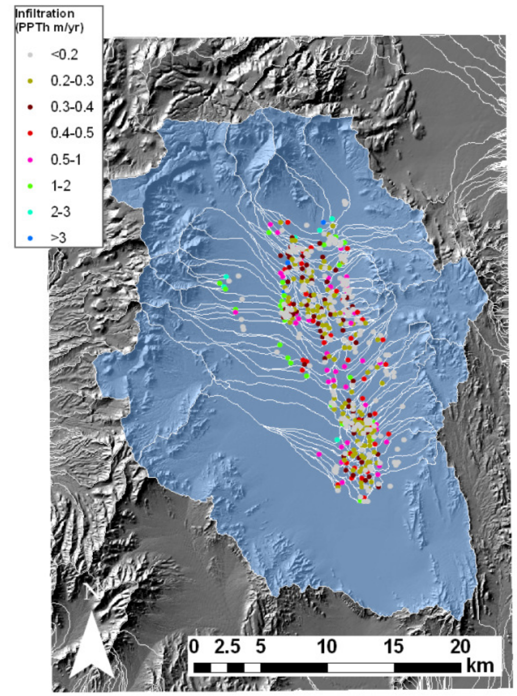
Linked file: MCL Normalized Cavity Concentration vs Time.pdf

Figure 2-6 MCL Normalized Cavity Concentration versus Time

Flow & Transport Model - UZ

- UZ testing area represented with 12 separate computational grids
- Grids are highly discretized around subsidence craters, collapse chimneys, cavities, and faults
- Water-accessible radionuclide inventory directly input into “exchange volumes” surrounding detonations
- Apply estimates of crater infiltration due to overland flow based on GIS studies of crater attributes and stochastic rainfall/runoff/infiltration models

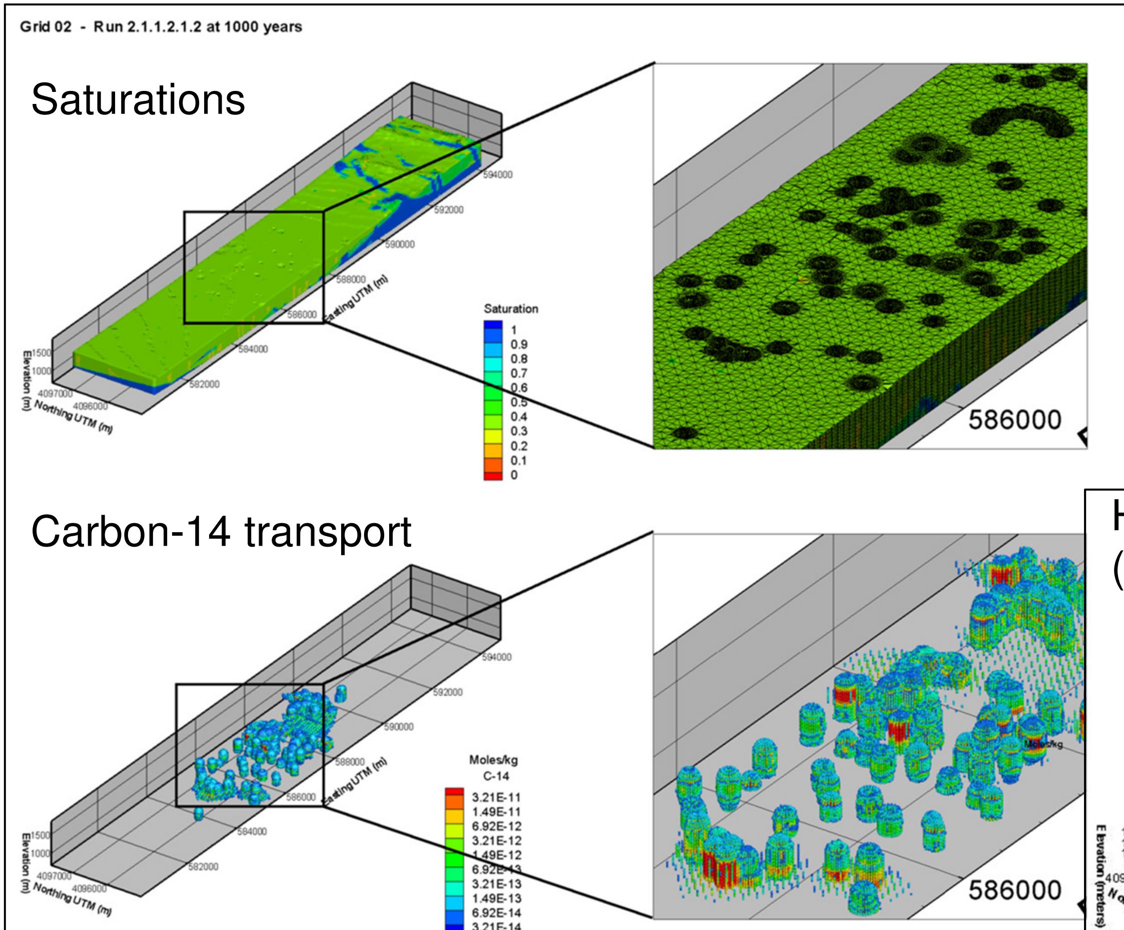




N-I, 2013 (Fig. 3-16)

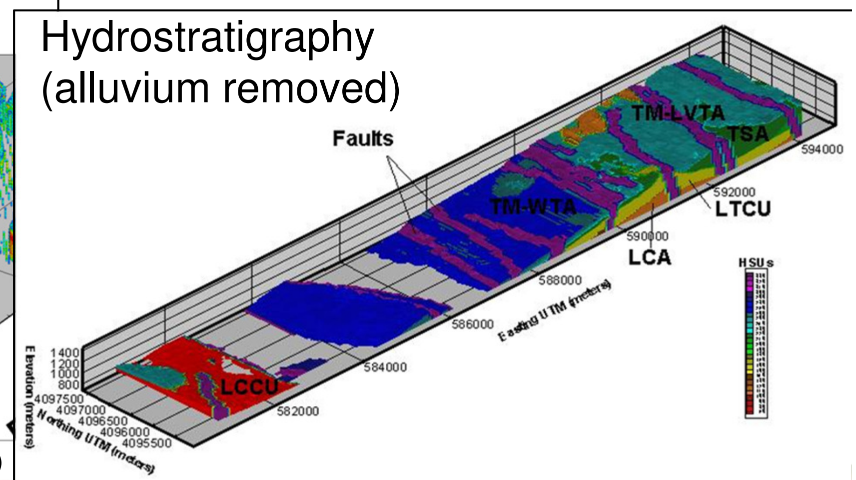
Photo by Greg Pohll (N-I, 2013 [Fig. E-17])

Example Model Results: Grid 2



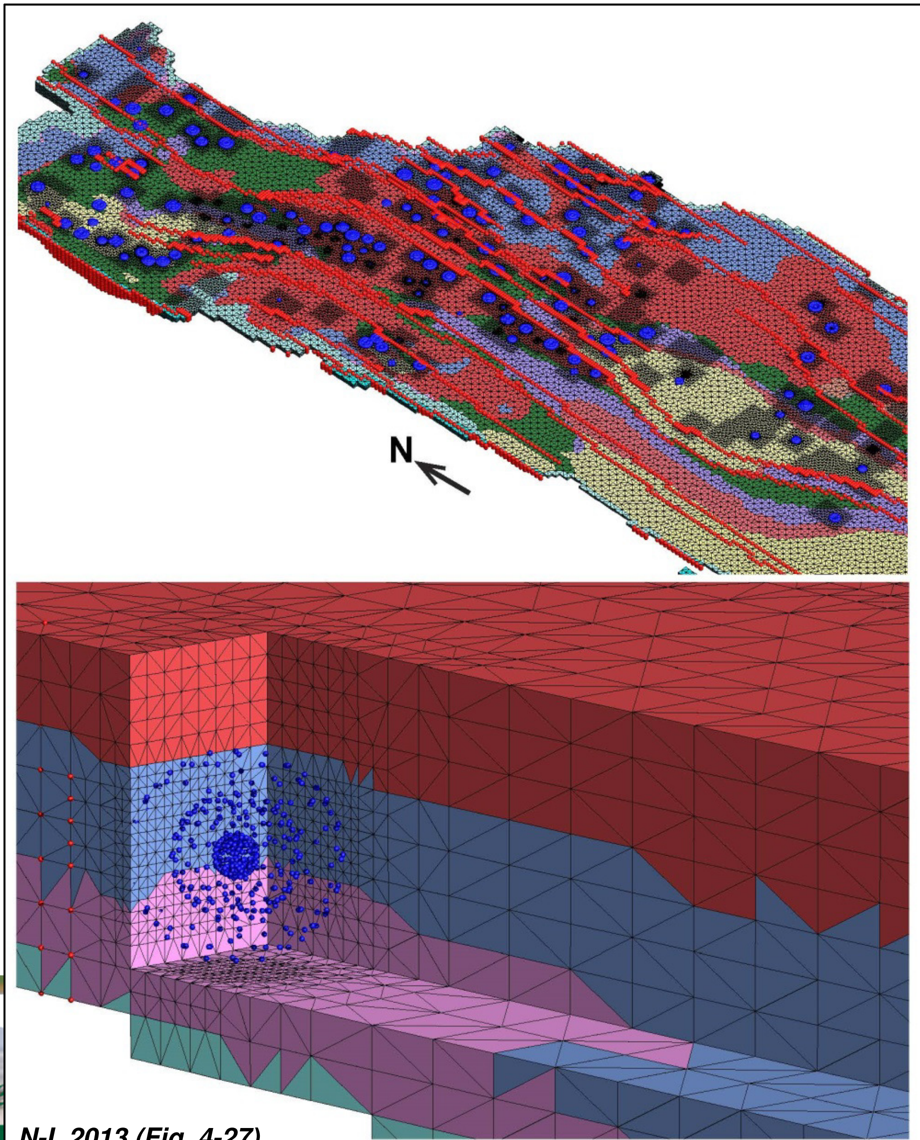
N-I, 2013 (Fig. 3-30)

- Thick alluvium in center of basin
- Faults assumed not to cross-cut alluvium



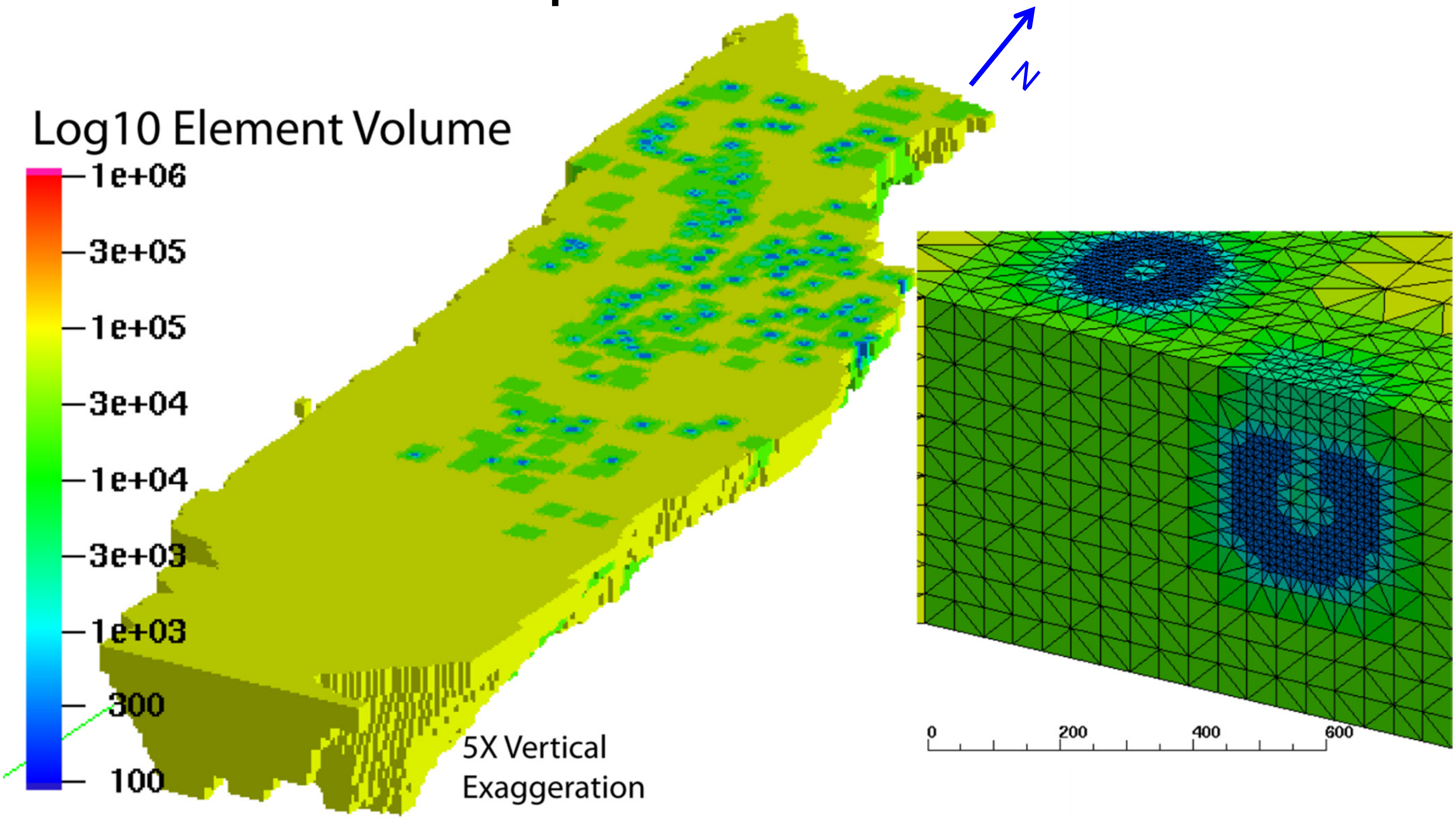
SZ Alluvial/Volcanic Model

- Model uses sophisticated grid to represent initial radionuclide distribution around 76 detonations with working points in SZ alluvial/volcanic system
- Considers alternative testing effects models and alternative flow and transport pathways to LCA (faults and test-induced pathways)
- Incorporates water and radionuclide fluxes arriving from UZ model simulations



N-I, 2013 (Fig. 4-27)

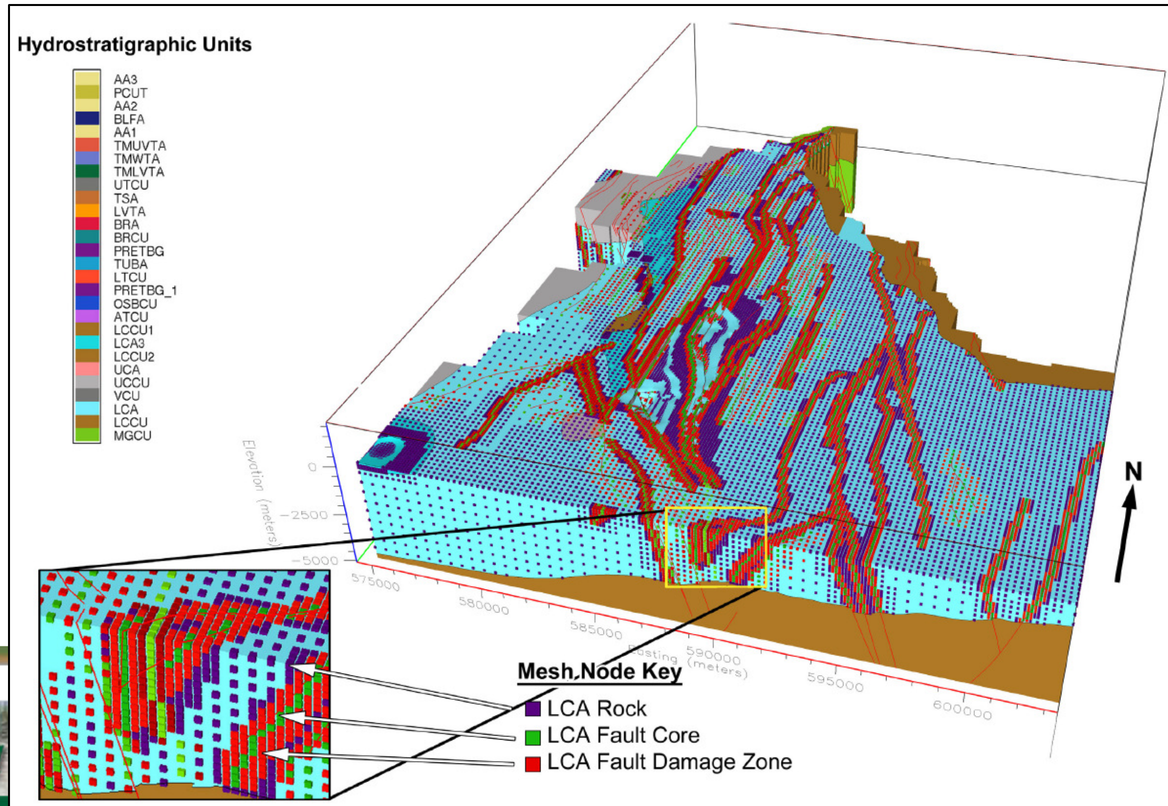
SZ Alluvial/Volcanic Model Computational Mesh



N-I, 2013 (Fig. 4-9)

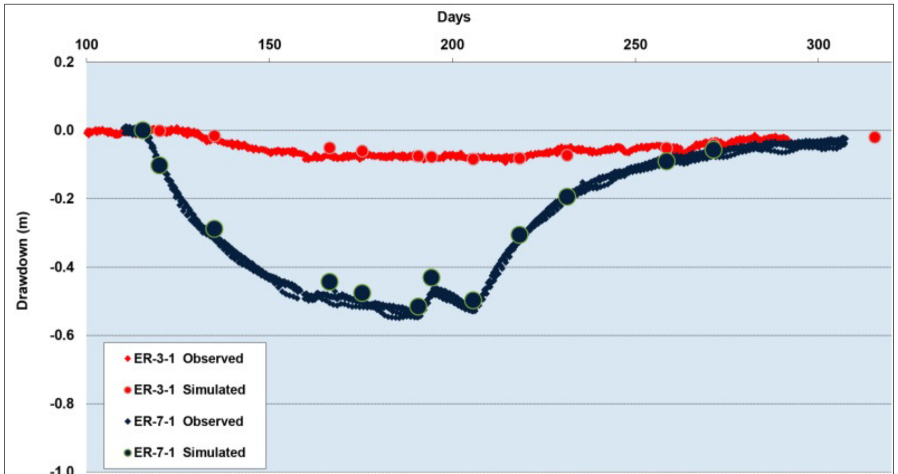
LCA Flow and Transport Model

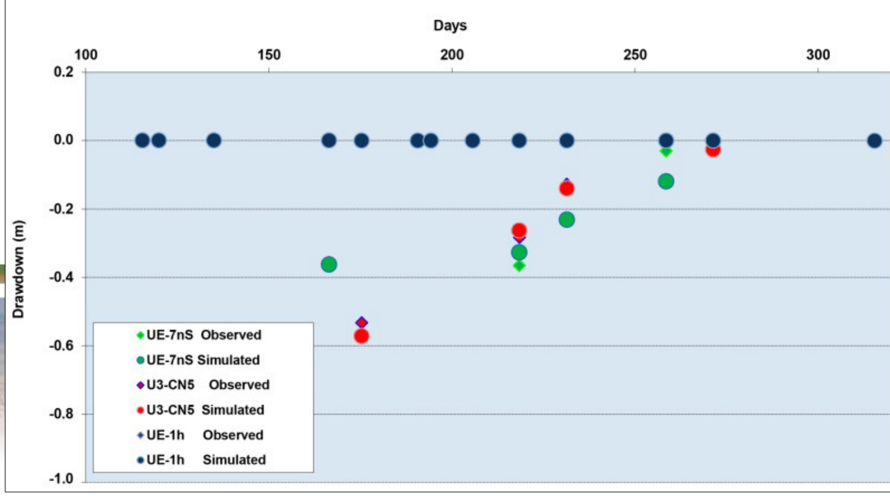
- 106 faults or fault segments directly incorporated into the LCA flow and transport model as possible flow and transport pathways
- Fault-zone architecture included consideration of:
  - Low-permeability fault cores containing gouge
  - Highly fractured and permeable fault damage zones
  - Country rock with background fracture density and permeability



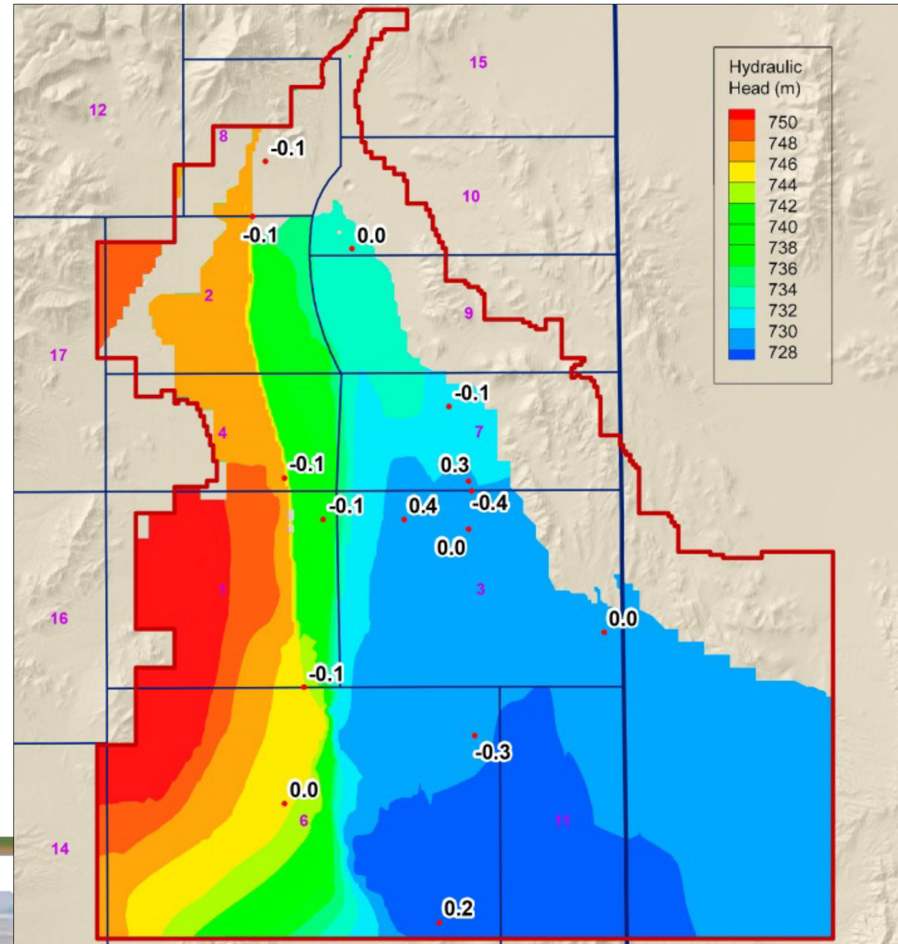
LCA Flow Model - Calibration

Transient MWAT Drawdown Calibration





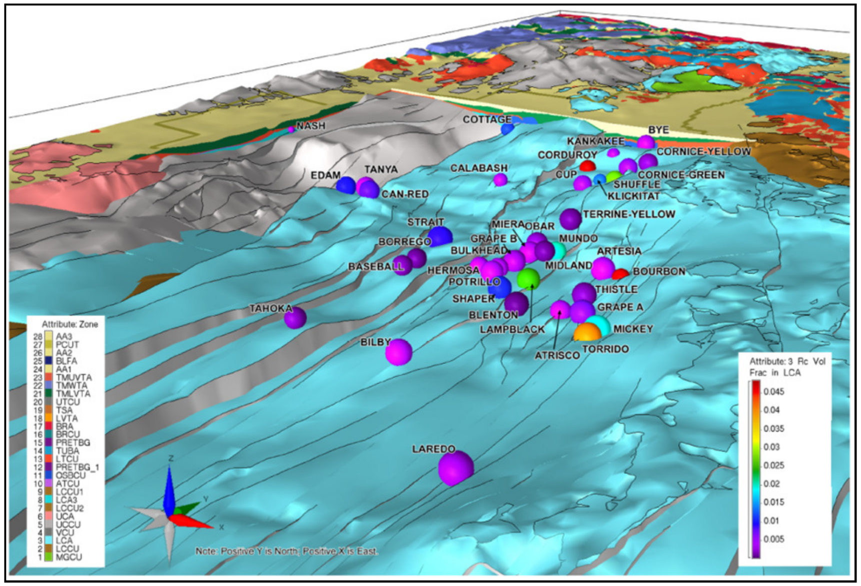
Steady-State Head Calibration



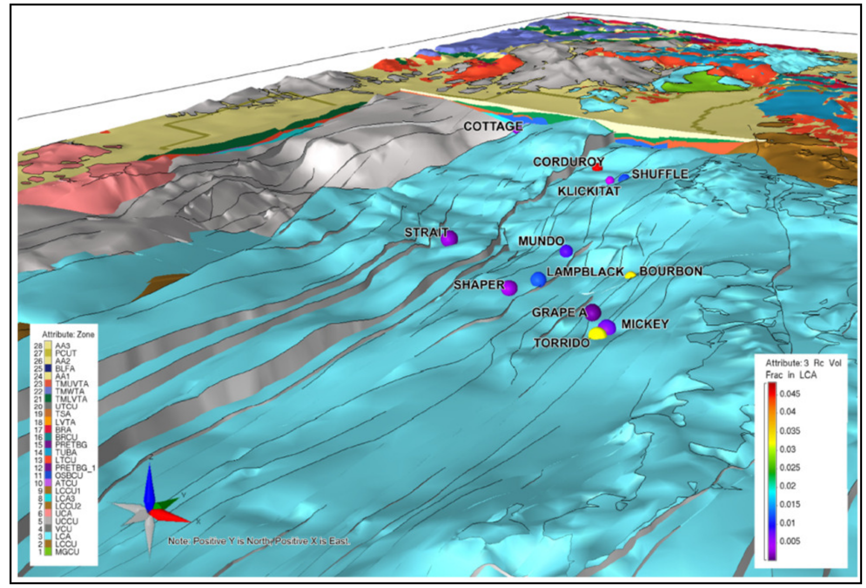
LCA Transport Model

- Incorporated radionuclide inputs from both UZ and SZ alluvial/volcanic models, as well as that part of the radionuclide inventory initially emplaced at the top of the LCA
  - Superposition of different radionuclide sources to create either partial or integrated contaminant boundary
- Conceptual model uncertainty (e.g., LCA continuity north of Yucca Flat, exchange volume radius) and parametric uncertainty (e.g., fracture frequency in faults and country rock) included to produce multiple contaminant boundaries

LCA Radionuclide Sources



N-I, 2013 (Fig. 2-3)



N-I, 2013 (Fig. 2-2)

- Number of detonations with exchange volumes that initially intersect the LCA depends on the assumed size of the exchange volume
  - 12 detonations with a 2 R_c and 39 detonations with a 3 R_c exchange volume
- In either case, the radionuclide mass initially emplaced in the LCA is much less than 1% of the total Yucca Flat inventory

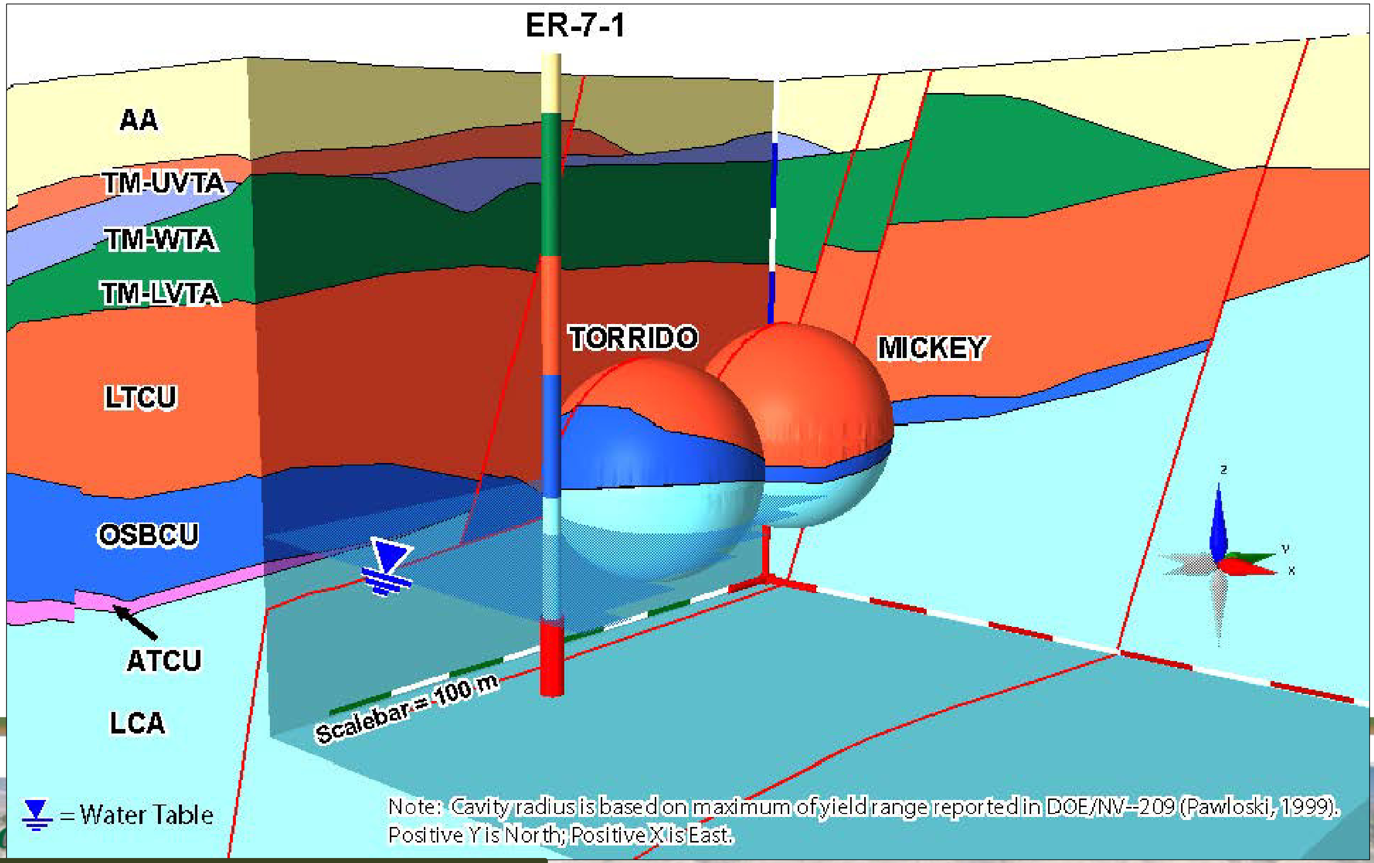
Cavity radius is calculated using the maximum of the announced yield range in DOE/NV--209 (2000) and the equation in Pawloski (1999).

Example Radionuclide Sources

- TORRIDO
  - 1969
  - 20–200 kt
  - 515 meters*
  - 71 meter cavity radius (estimated)
- MICKEY
  - 1967
  - 20–200 kt
  - 500 meters*
  - 72 meter cavity radius (estimated)

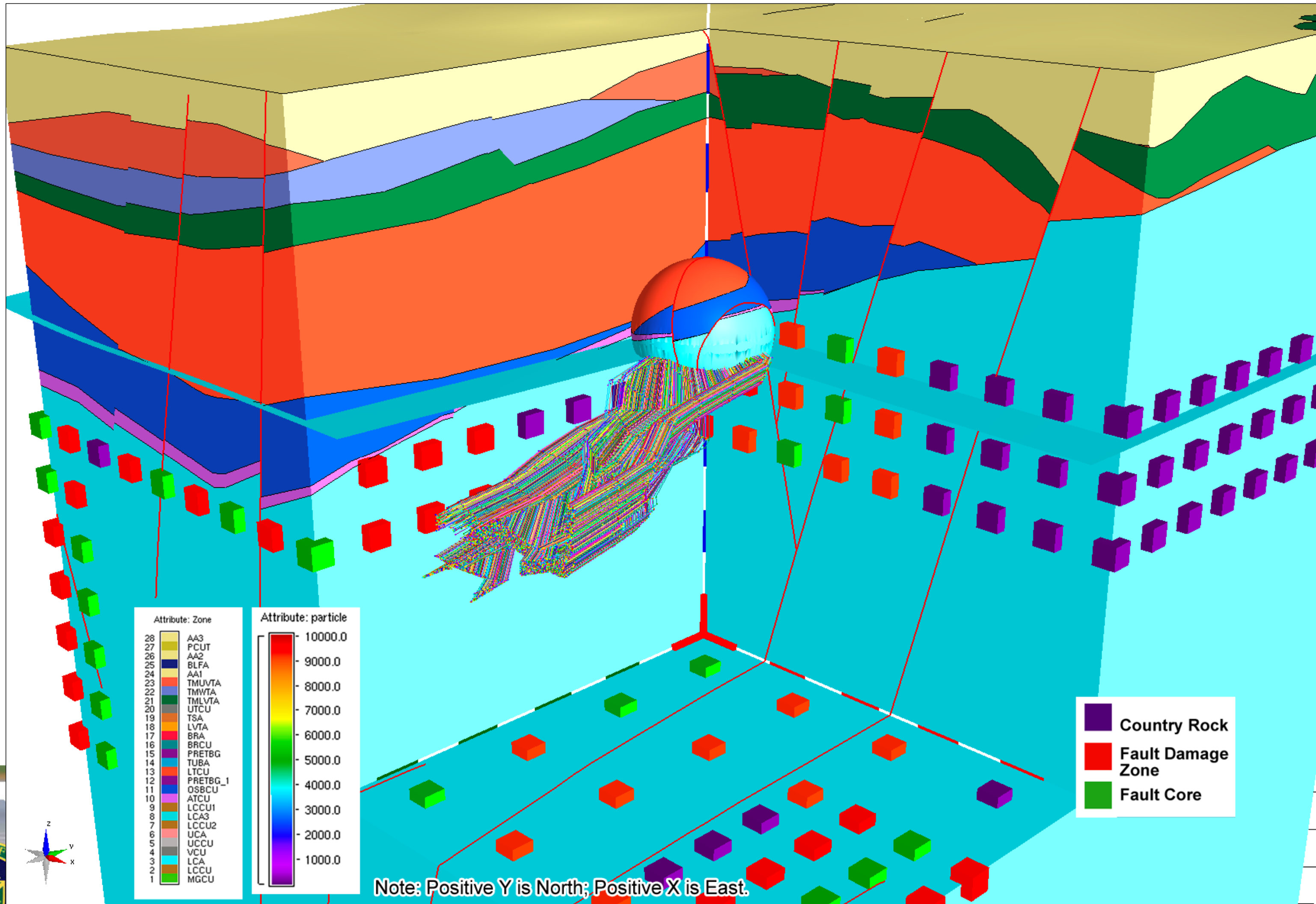
*Working point depth

- ER-7-1
  - Located 200 meters and 500 meters downgradient of TORRIDO and MICKEY, respectively
  - Tritium reported as 117 pCi/L



Cavity radius is calculated using the maximum of the announced yield range in DOE/NV--209 (2000) and the equation in Pawloski (1999). 2 Rc shown in figure.

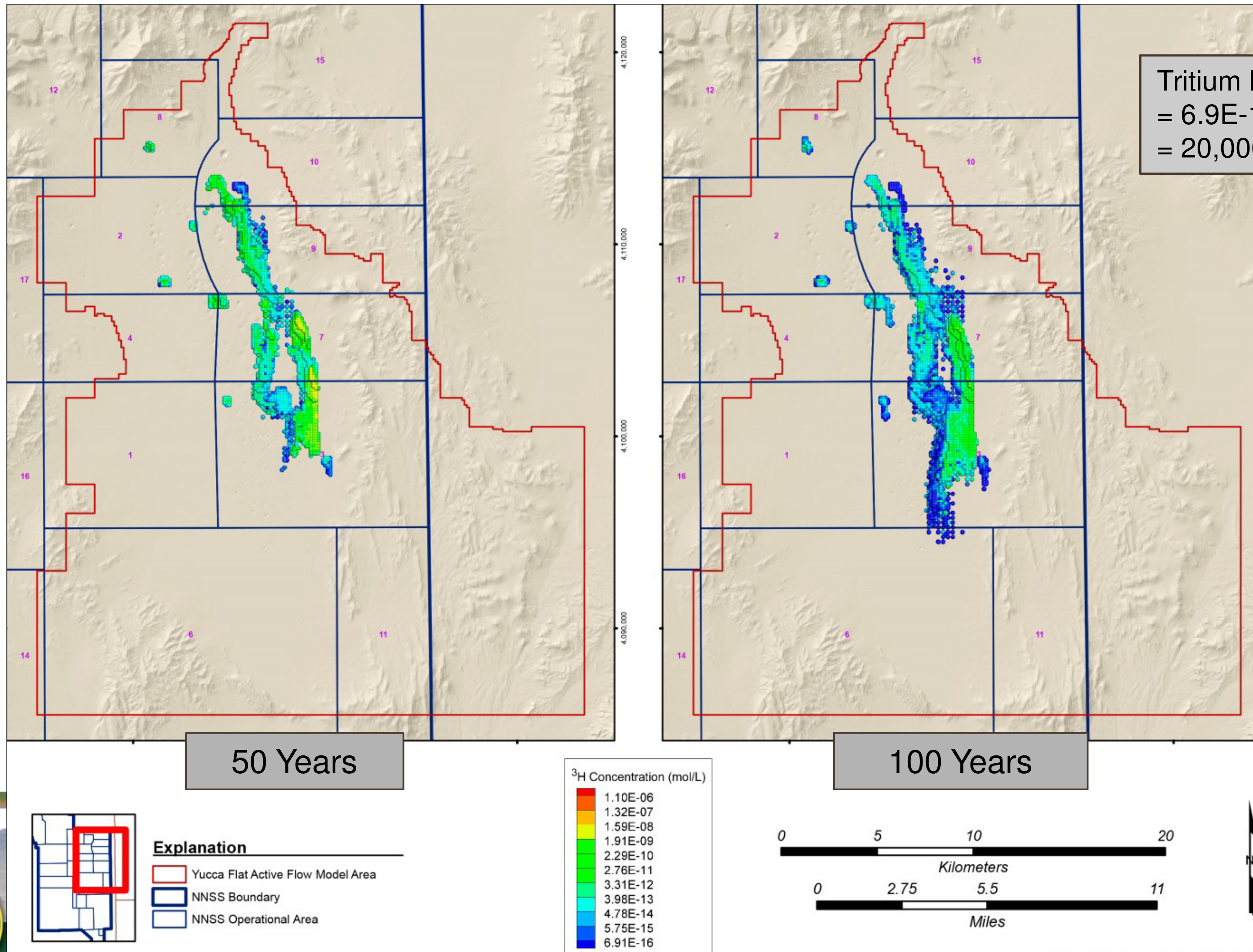
Example Particle Trajectories BOURBON



N-I, 2013 (Fig. 6-28)

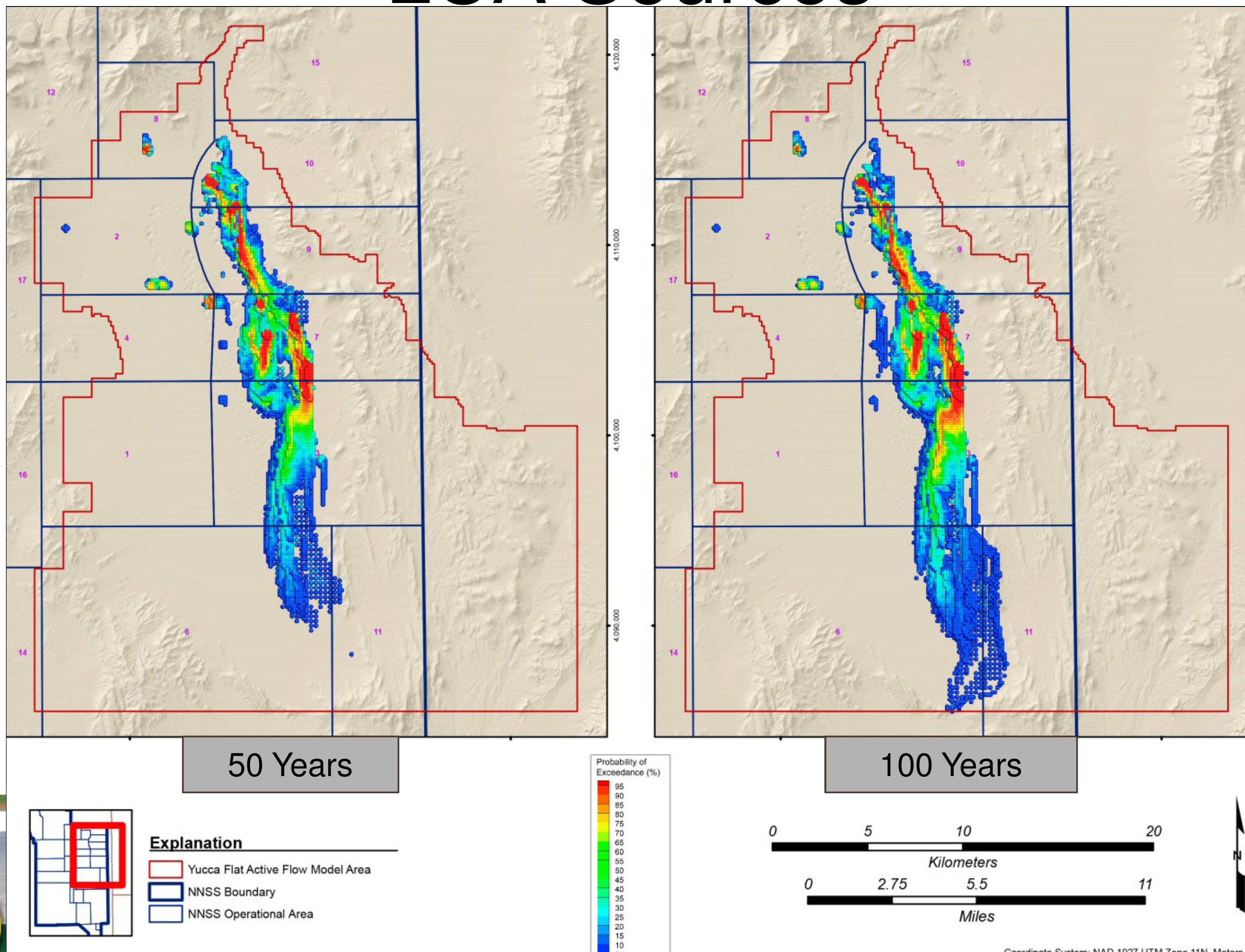
Base Case Tritium Concentrations - LCA Sources

Tritium MCL
= 6.9E-13 mol/L
= 20,000 pCi/L



N-I, 2013 (Fig. 6-59)

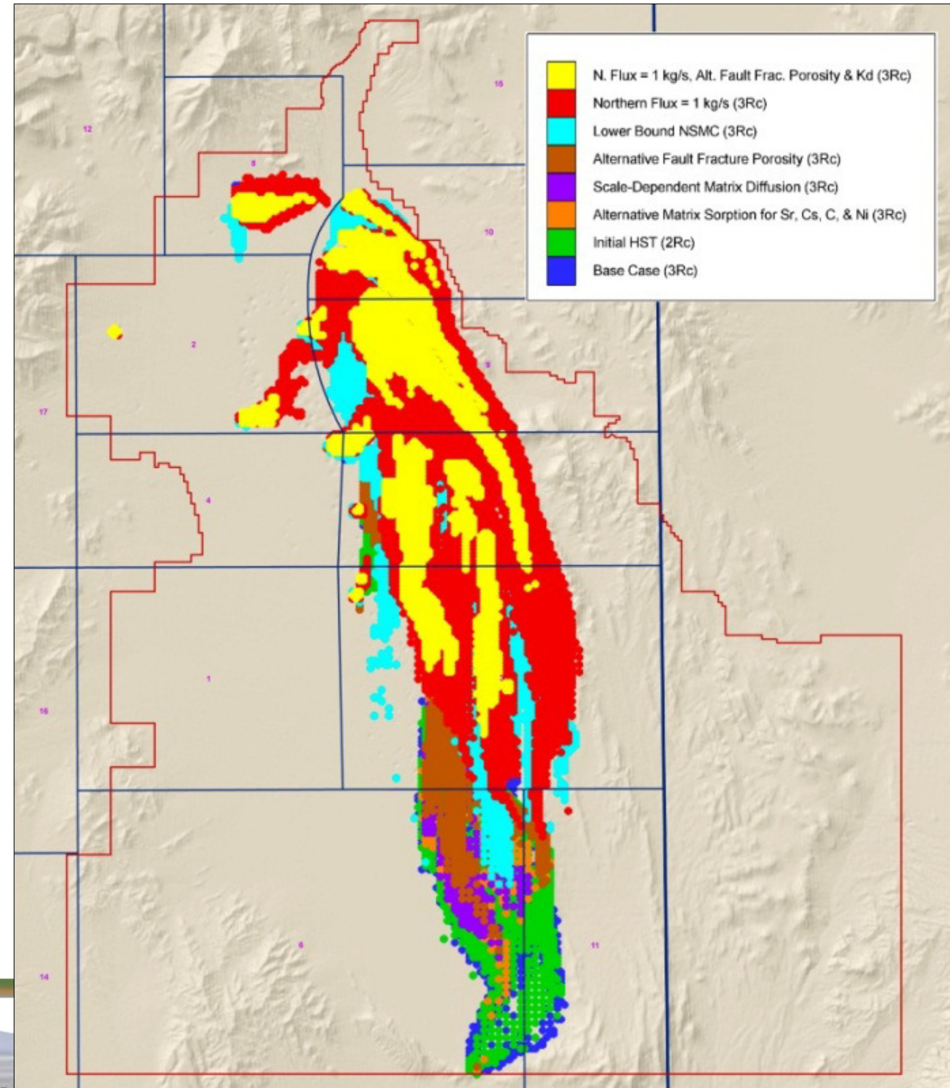
Base Case Probability of Exceeding MCL - LCA Sources



N-I, 2013 (Fig. 6-62)

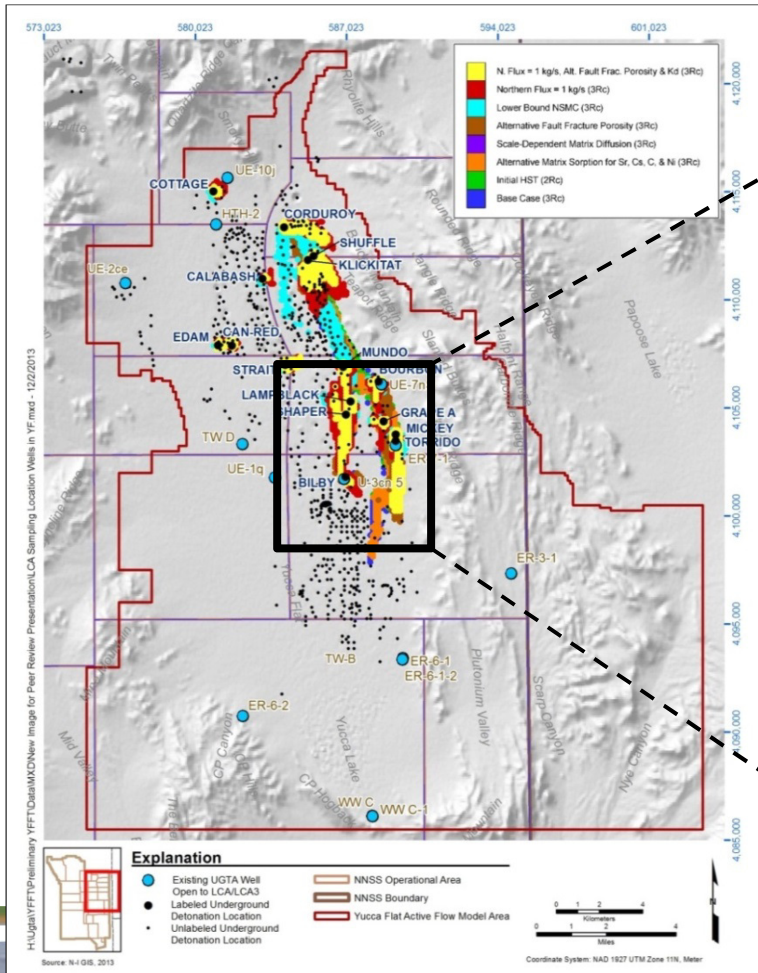
Ensemble Contaminant Boundaries

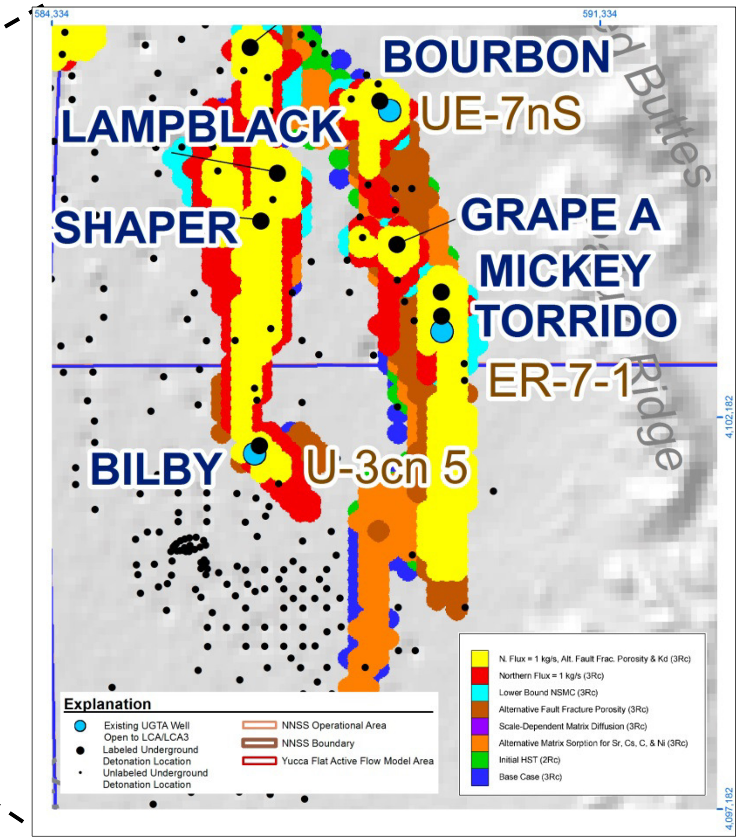
- Range of possible contaminant boundaries for alternative models:
  1. Combined low flux from north with alternative fault damage zone fracture properties and K_d
  2. Low water flux from north
  3. Lowerbound Null Space Monte Carlo flow field
  4. Alternative fault damage zone fracture properties
  5. Alternative scale-dependent matrix diffusion
  6. Alternative K_d for strontium, cesium, carbon and nickel
  7. Alternative hydrologic source term
  8. Base case



N-I (2013, Fig. 6-99)

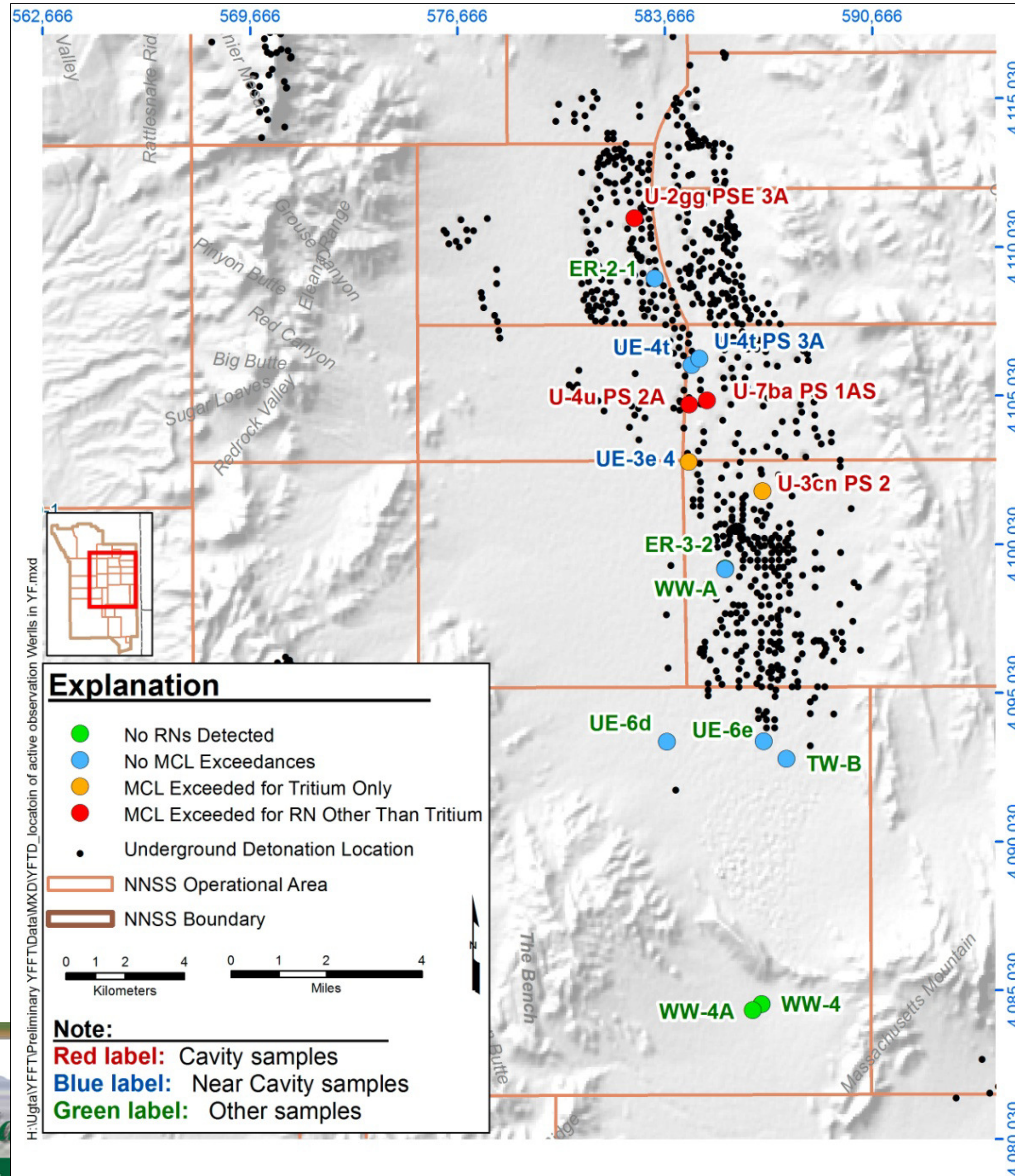
Cells with Greater Than 50% MCL Exceedance at 50 Years – LCA Sources





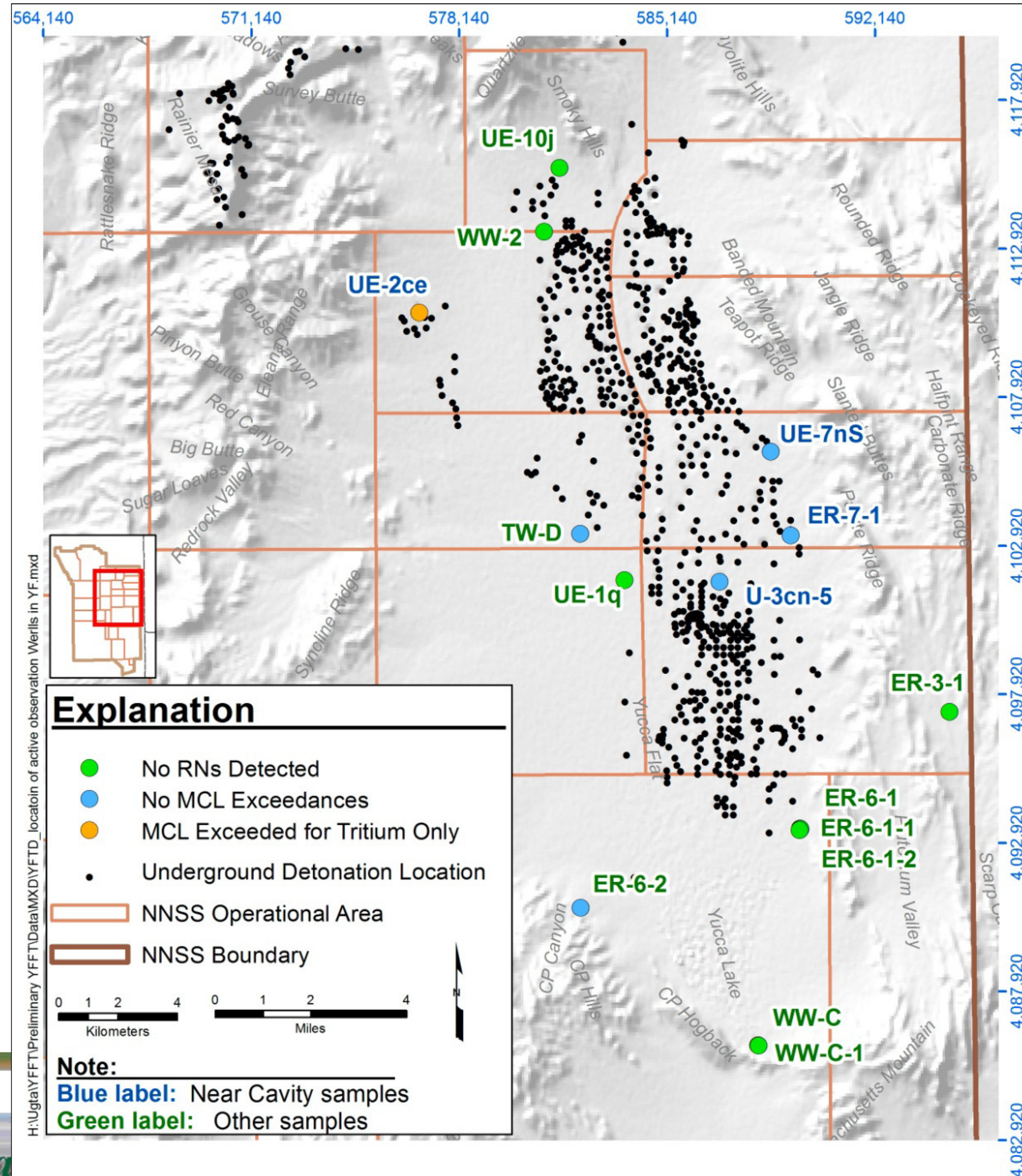
Modified from N-I (2013, Fig. 6-103a)

Observation Wells Completed in Alluvial and Volcanic Rock Aquifers



Observation Wells Completed in Carbonate Aquifers

- Model results over predict observed low concentrations near several contaminant sources (BOURBON, TORRIDO, BILBY) at U-3cn-5, UE-7nS, and ER-7-1
- Model results are consistent with observed high concentrations near NASH at UE-2ce



Summary

- Underground testing from 1960's to 1992 left residual contamination in and around test cavities on NNSS
- Process for closure of UGTA CAUs developed and implemented during the last 20 years
  - Frenchman Flat about to enter closure
  - Yucca Flat about to enter CADD/CAP
  - Rainier Mesa/Shoshone Mountain about to complete modeling
  - Central/Western Pahute Mesa about to complete characterization and start modeling
- Drilling, testing, analysis and modeling provide basis for closure decisions (use restriction, monitoring)
- Active participation by NDEP in planning (CAIP and CADD/CAP) and reviews has greatly aided acceptance
- Iterative process of model development and testing with direct inclusion of uncertainty in models and parameters

UGTA Next Steps

- Frenchman Flat CAU
  - Develop Closure Report
  - Initiate Long-Term Monitoring and Institutional Controls
- Rainier Mesa/Shoshone Mountain CAU
  - Complete Flow and Transport Model Report
  - Conduct Peer Review
- Yucca Flat CAU
  - Complete Peer Review
  - Develop CADD/CAP
  - Initiate Model Evaluation Studies
- Central/Western Pahute Mesa CAU
  - Complete Corrective Action Investigations
  - Initiate Flow and Transport Model