U.S. Department of Energy
Office of Civilian Radioactive Waste Management

YUCCA MOUNTAIN PROJECT

# Saturated Zone Flow and Transport Processes

Presented to:
**Nuclear Waste Technical Review Board**

Presented by:
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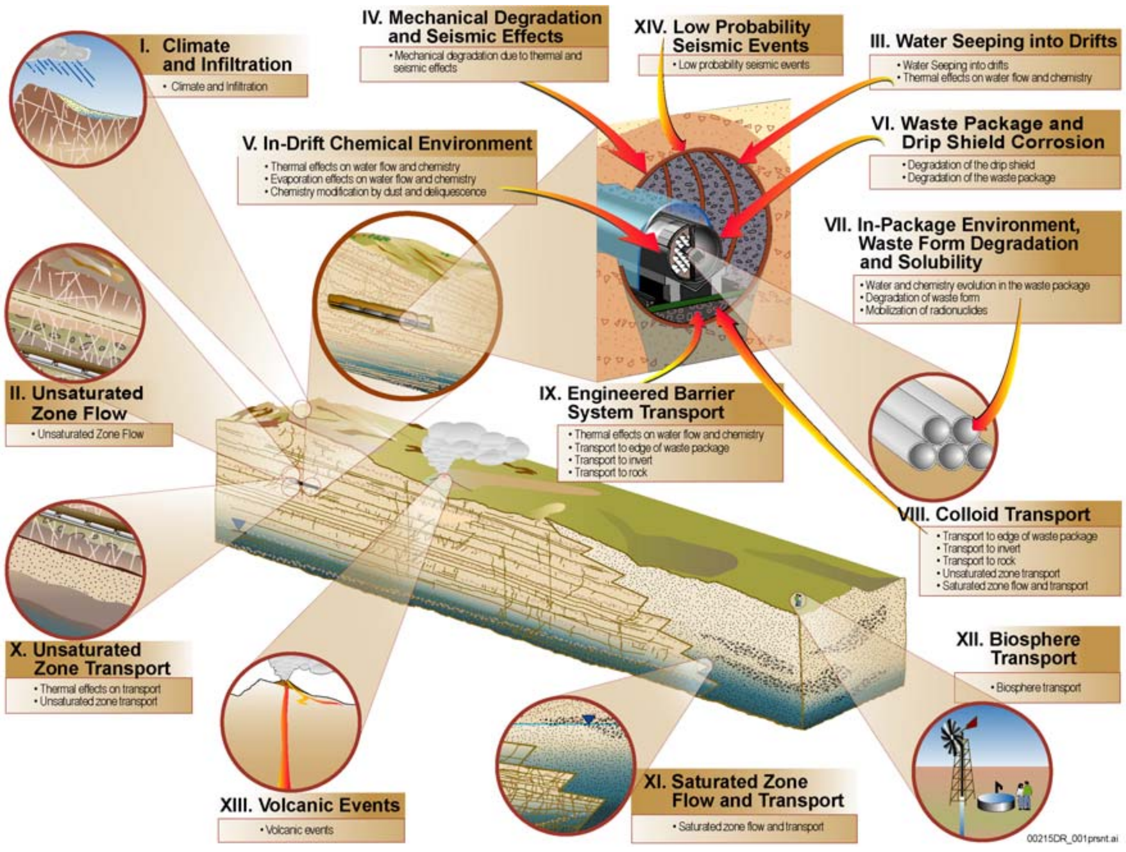
**September 16, 2003**
**Amargosa Valley, Nevada**

# Outline

- Introduction - Objectives
- Regional Ground-water Flow Processes
- Regional Hydrochemistry
- Site Scale Ground-Water Flow Processes
- Site-Scale Radionuclide Transport Processes
- Results of Radionuclide Transport Model
- Comparison to Alternative Model
- Summary and Conclusions

# Components Affecting Technical Basis of Post-Closure Safety Analysis



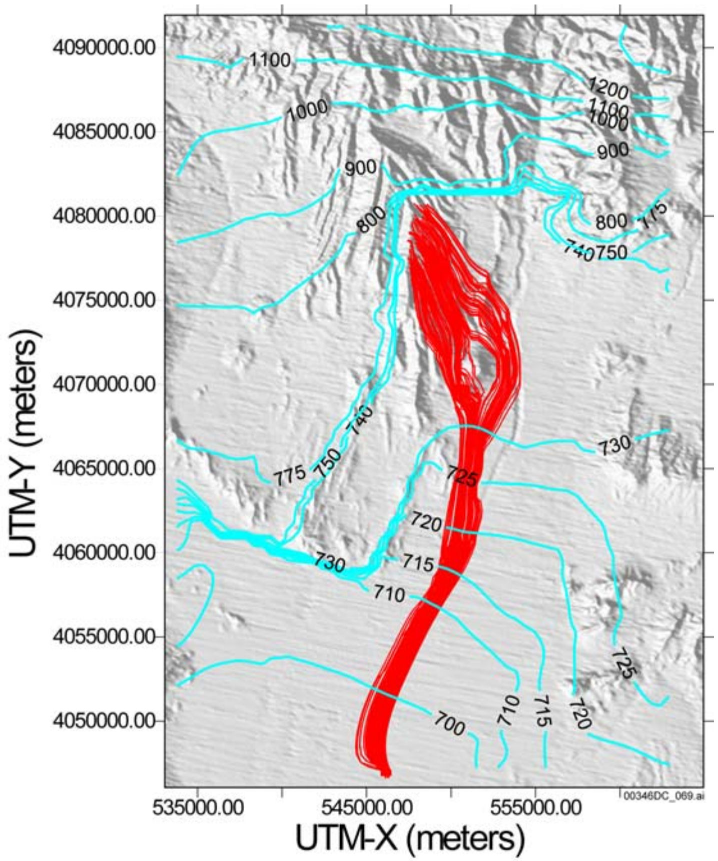

- Saturated zone flow and transport is one of 14 components of post closure safety
- Saturated zone provides pathways for potential release of radionuclides to reasonably maximally exposed individual
- Saturated zone affects performance in both nominal scenario class and disruptive event scenario classes initiated by seismic and volcanic events

# Introduction

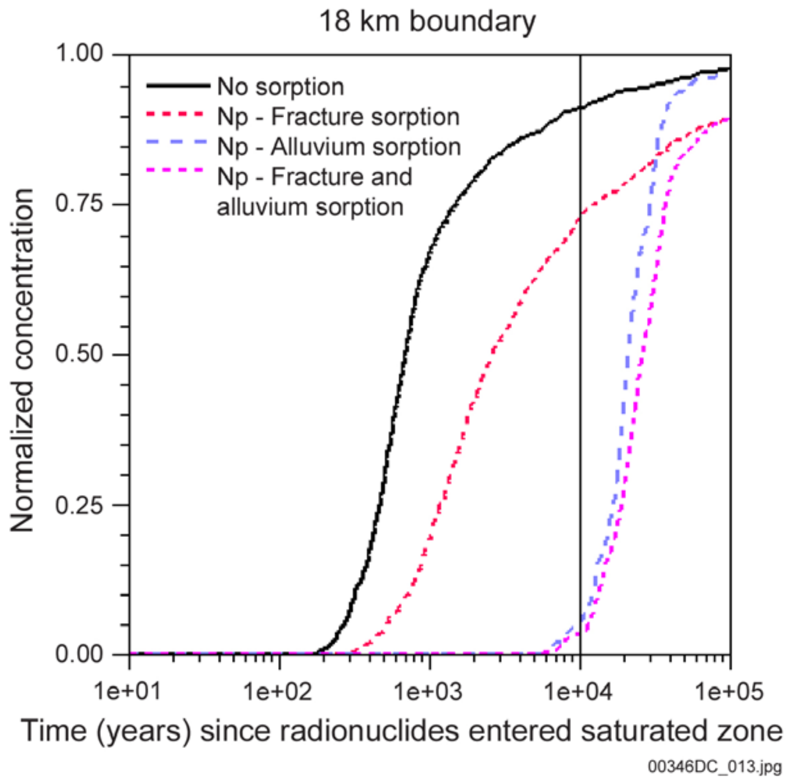
- **Saturated zone flow defines the flow paths and flow rates of ground-water from where radionuclides are potentially released from unsaturated zone to where they are used by hypothetical person (the reasonably maximally exposed individual of 40 CFR Part 197 and 10 CFR Part 63)**
- **Saturated zone transport defines the advective-dispersive transport velocities of any radionuclides potentially released from the unsaturated zone and their transport times, including the effects of matrix diffusion and retardation, along the paths of likely ground-water flow**
- **Performance measure of interest is mass (or activity) flux at point of compliance (about 18 km south of Yucca Mountain)**
- **The bases for quantifying the above processes relies on site-specific hydrogeologic, geochemical and transport testing conducted by numerous scientists over the last 20+ years**

# Introduction –
## Performance Assessment Use of Saturated Zone Flow and Transport Analyses

### Groundwater Flow Paths from Yucca Mountain




### Advective Dispersive Mass Breakthrough Curves to Compliance Boundary



# Key Documents Describing Technical Basis

**D'Agnese, F.A., O'Brien, G.M., Faunt, C.C., Belcher, W.R., and SanJuan, C., 2002. *A Three-Dimensional Numerical Model of Predevelopment Conditions in the Death Valley Regional Ground-Water Flow System, Nevada and California.* Water-Resources Investigations Report 02-4102.**

**USGS, 2001. *Water-Level Data Analysis for the Saturated Zone Site-Scale Flow and Transport Model.* ANL-NBS-HS-000034, Rev 00, ICN 01.**

**Hevesi, J.A., Flint, A.L., and Flint L.E., 2002. *Preliminary Estimates of Spatially Distributed Net Infiltration and Recharge for the Death Valley Region, Nevada-California.* Water-Resources Investigation Report 02-4010.**

## Analyses and Model Reports (in development):

***Saturated Zone In-situ Testing* (Reimus, P. and M.J. Umari)**

***Geochemical and Isotopic Constraints on Groundwater Flow Directions and Magnitudes, Mixing and Recharge at Yucca Mountain* (Kwickles, E. and R. Robeck)**

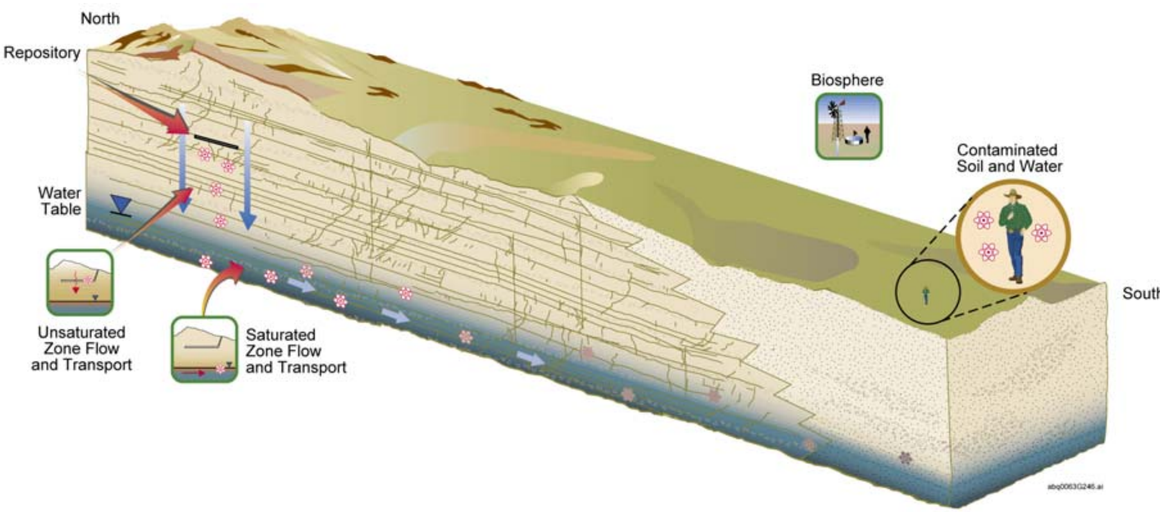
***Site-Scale Saturated Zone Flow Model* (Eddebbarh, A.A. and Zyvoloski, G.)**

***Site-Scale Saturated Zone Transport Model* (Kelkar, S. and Robinson, B.)**

***Saturated Zone Colloid Transport Model* (Viswanathan, H.)**

***Saturated Zone Flow and Transport Abstractions* (Arnold, B.W. and Kuzio, S.)**

# Conceptual Framework for Saturated Zone Flow and Transport Processes

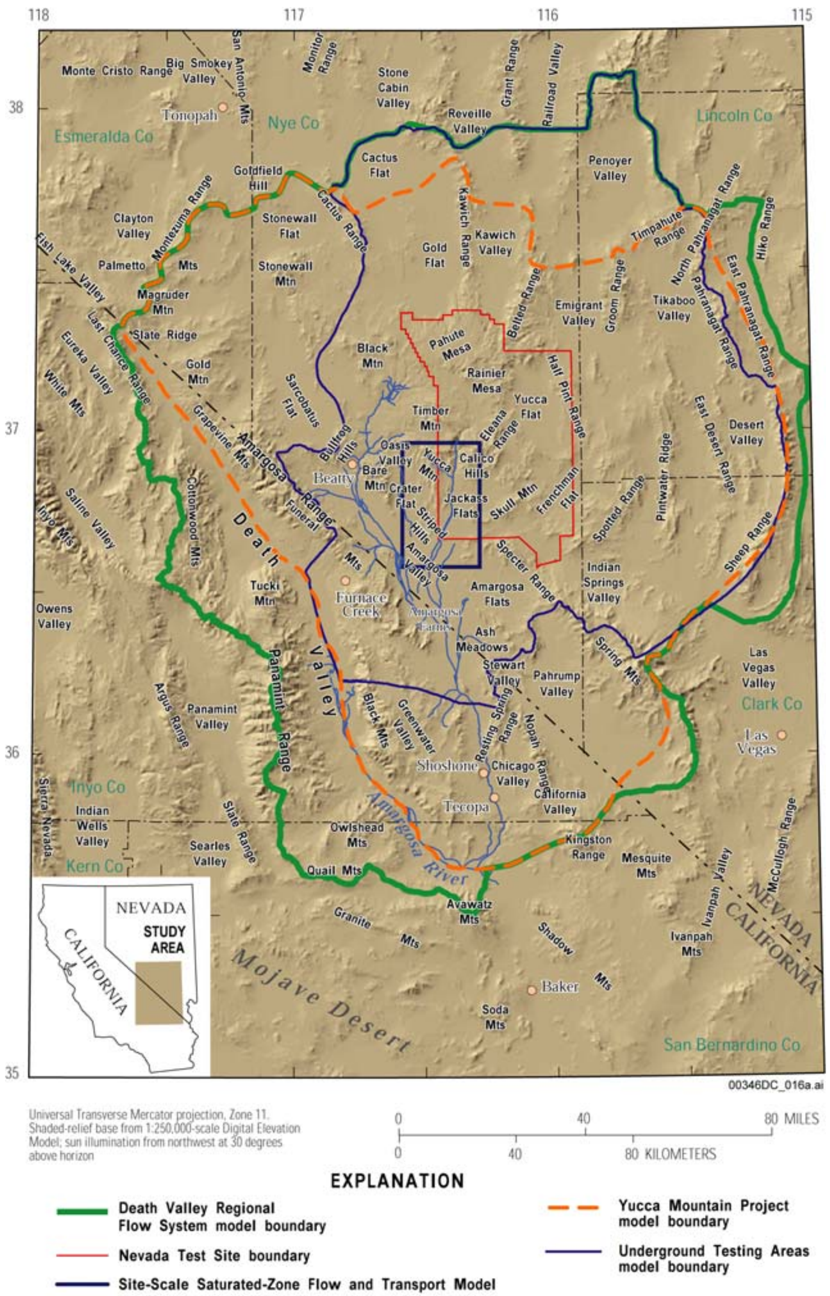



- **Radionuclides potentially released from unsaturated zone are transported through saturated zone to point of compliance**
- **Flow paths determine the geologic units likely to be contacted by radionuclide-bearing groundwater**
- **Portion of flow and transport in fractured tuff and portion in porous alluvium**

# Regional Hydrogeology

- Regional groundwater flow system investigated by USGS and other scientists for 20+ years
- Regional groundwater flow characterized by representations of
  - relevant physiographic features,
  - recharge/discharge locations/amounts,
  - regional geology,
  - regional potentiometric surfaces and
  - regional geochemistry
- Result of regional characterization indicates general groundwater flow paths and flow rates in vicinity of Yucca Mountain

# Major Physiographic Features of Death Valley Regional Flow System




- Death valley region encompasses about 70,000 km$^2$
- Major features include Spring Mountains, Death Valley, and Amargosa Valley
- Region is an enclosed hydrologic basin
- Different boundaries used for different regional modeling studies

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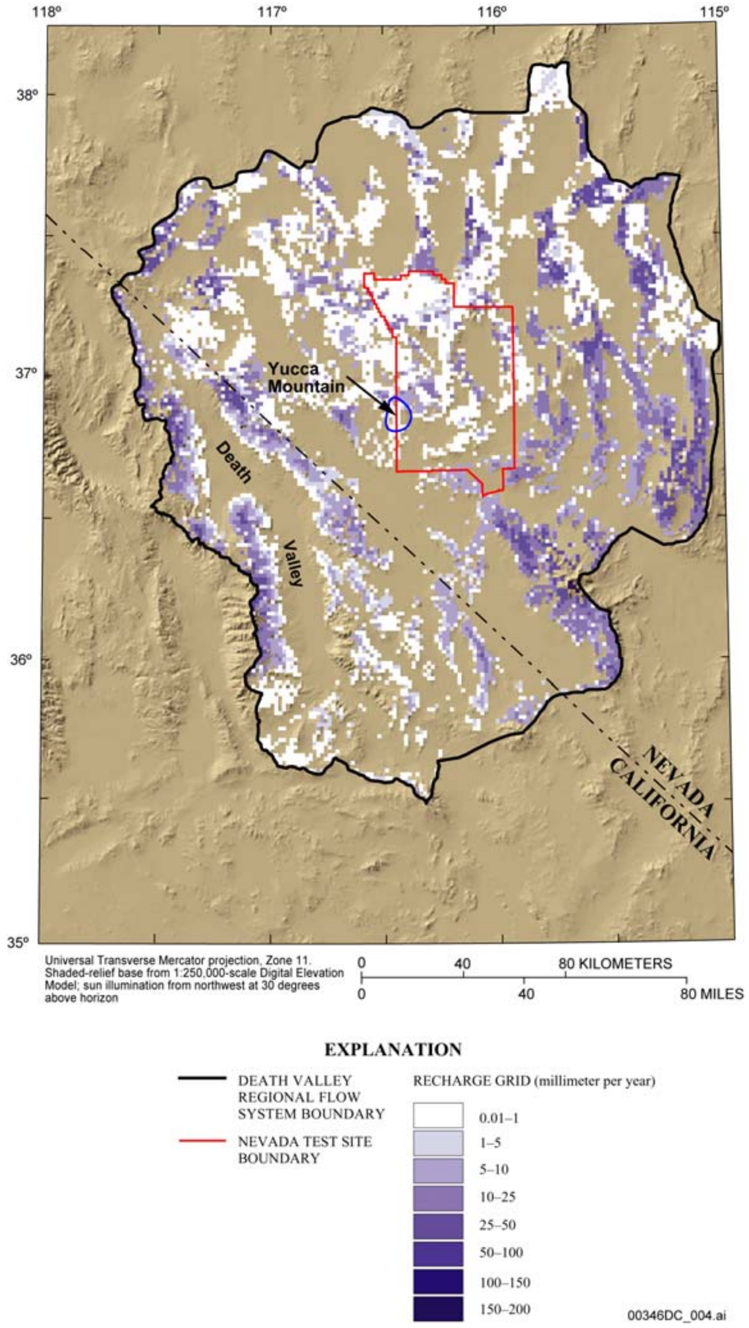


# Major Recharge within Death Valley Regional Flow System

- **Recharge generally occurs at topograpphic elevations greater than 1500 m asl**
- **Recharge a function of precipitation, slope, geology, and vegetation**
- **Uncertainty in recharge depending on estimation method**

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# Cumulative Recharge Estimates in Death Valley Regional Flow System

| Precipitation Model | Model Type | Average Value for Area of Death Valley Groundwater Flow Model (mm/yr) | Total Area Volume (million $m^3$/yr) | Net Infiltration or Recharge as a Percentage of Precipitation |
|---|---|---|---|---|
| 1980 to 1995 Modeled Precipitation | | 202 | 7,980 | — |
| | Model net infiltration | 7.8 | 310 | 3.9 |
| | Model net infiltration of areas with >200 mm/yr precipitation | 4.8 | 190 | 6.2 |
| | Modified Maxey-Eakin estimated recharge | 6.3 | 250 | 3.1 |
| | Modified Maxey-Eakin of areas with >200 mm/yr precipitation | 2.6 | 110 | 5.1 |
| | Original Maxey-Eakin estimated recharge | 4.8 | 190 | 2.4 |
| 1920 to 1993 Cokriged Precipitation | | 188 | 7,430 | — |
| | Modified Maxey-Eakin estimated recharge | 5.1 | 200 | 2.7 |
| | Original Maxey-Eakin estimated recharge | 3.7 | 150 | 2.0 |

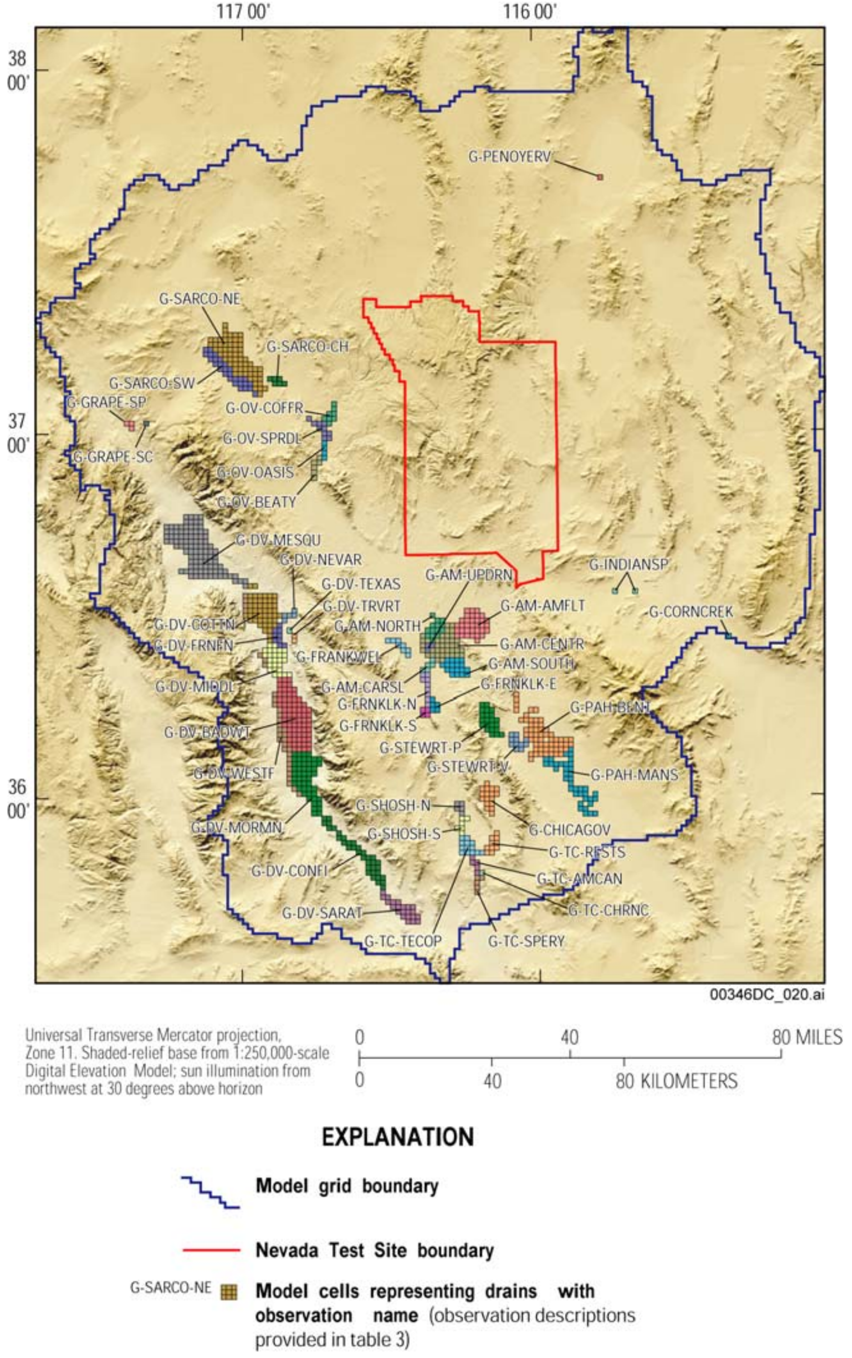
Source: Based on Hevesi et al. 2002 , Table 2).

NOTE: Volumetric flows rounded to the nearest 10 million $m^3$/yr.

# Time Out for a Comparison of Commonly Used Volumetric Flow Units

- **One million gallons per day = 1,100 Acre-foot per year**
- **One million gallons per day = 1.4 million $m^3$/yr**
- **One acre-foot per year = 1250 $m^3$/yr**
- **One acre-inch = 27,000 gallons**

- **Average water consumption in Las Vegas is about 20,000 gallons per month per household or about 1000 $m^3$/yr (a little less than one acre-foot/year)**
- **3,000 acre-feet/year (3.7 million $m^3$/yr) is the annual water demand by the reasonably maximally exposed individual specified in 10 CFR 63.312**




# Discharge Locations in Death Valley Regional Flow System

- **Natural groundwater discharge occurs at topographic lows**
- **Significant discharge occurs from carbonate springs and evapotranspiration from shallow groundwater at playas**

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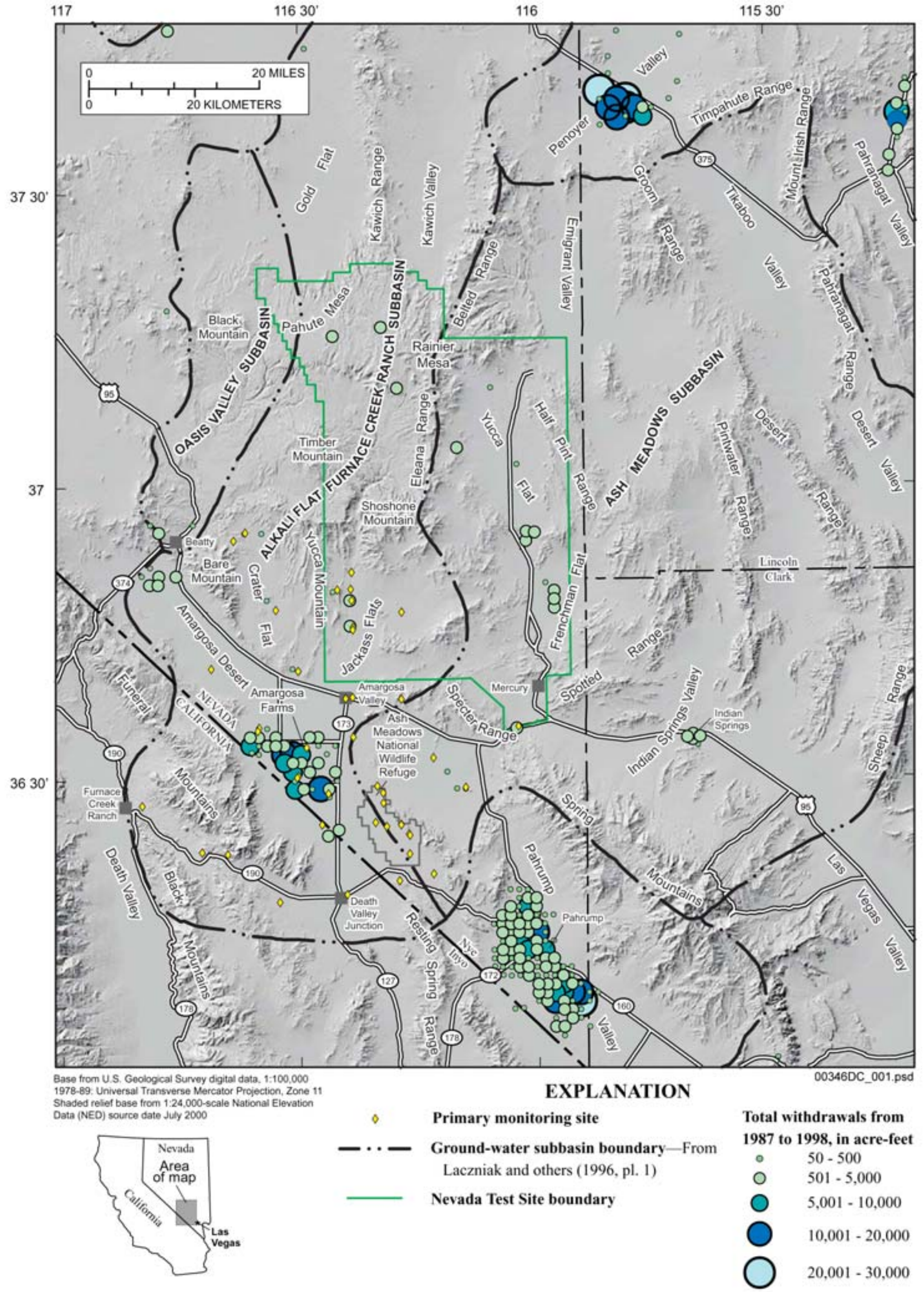
# Cumulative Regional Discharge Estimates in Death Valley Regional Flow System

| DISCHARGE REGION | ESTIMATED DISCHARGE (thousand $m^3$/day) | ESTIMATED DISCHARGE (million $m^3$/yr) |
|---|---|---|
| Death Valley | 92 | 32 |
| Ash Meadows | 61 | 22 |
| Sarcobatus Flat | 44 | 16 |
| Pahrump/Stewart Valley | 26 | 10 |
| Tecopa Basin | 21 | 8 |
| Oasis Valley | 20 | 7 |
| Penoyer Valley | 13 | 5 |
| Shoshone  Basin | 7 | 2 |
| Franklin Lake | 3 | 1 |
| Others | 8 | 3 |
| TOTAL | 295 | 106 |

Source:  Modified from D/Agnese et al., 2002

**Regional recharge and discharge estimates agree within a factor of 1 to 3**




# Groundwater Withdrawals in the Death Valley Regional Flow System

- **Groundwater used for irrigation, mining and domestic purposes**
- **Values presented are cumulative estimates over 12 years (1987 to 1998)**
- **To convert 12-yr cumulative withdrawals to average annual withdrawal in m3/yr multiply by 100**
- **NOTE - Subbasin boundary is different from regional flow system boundary**

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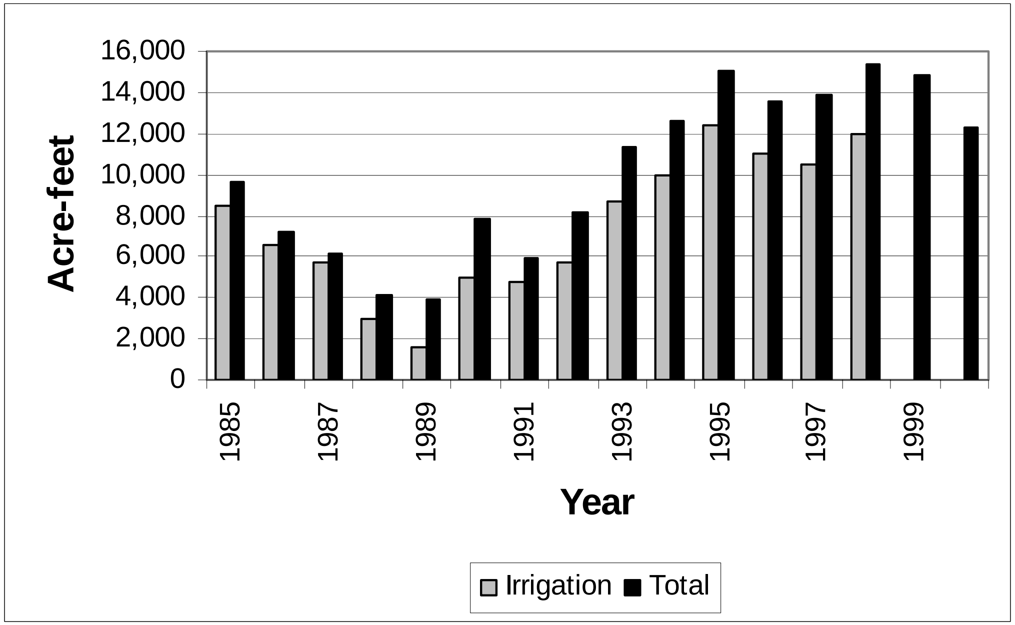
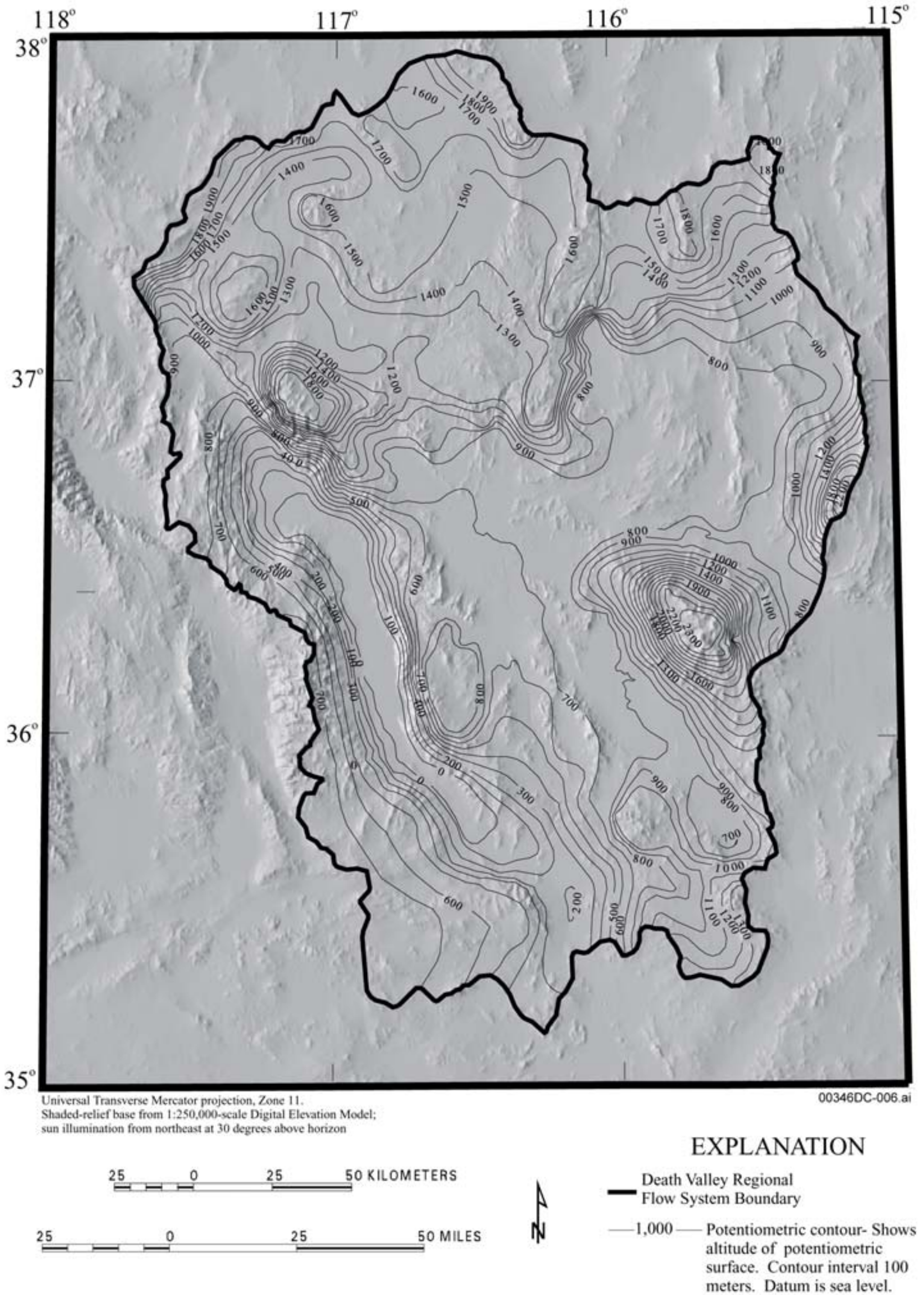
# Annual Groundwater Withdrawals in the Amargosa Valley Area




Annual water withdrawals in Amargosa Desert hydrologic basin (#230).

Sources: 1985–1997: Thiel Engineering Consultants 1999
1998–2000: Fenelon and Moreo, 2002 (Data on irrigation withdrawals not available for 1999–2000).

- **Irrigation water use comprises ~ 75% of total water use in Amargosa Valley**
- **About 2000 acres are commercially farmed in Amargosa Valley (more than 90% in alfalfa or other hay)**
- **Average water use is about 5 to 6 acre-ft per acre of alfalfa**

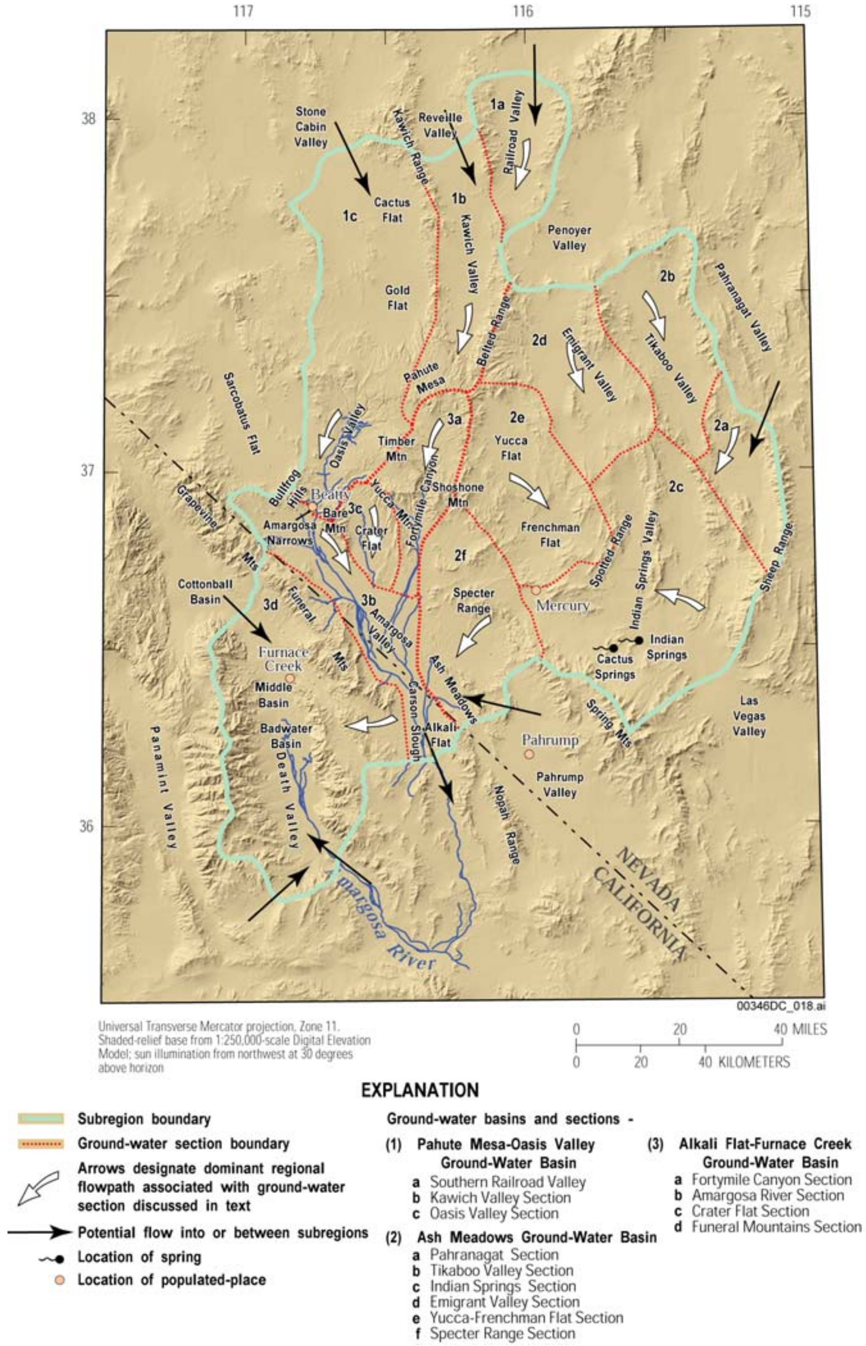



# Potentiometric Surface of Death Valley Regional Flow System

- **Potentiometric contours indicate significant recharge in Spring Mountains, Amargosa Range and Rainier Mesa**
- **Significant discharge in Death Valley**
- **Although this surface is indicative of regional trends, local anomalies exist**
- **NOTE: Regional flow system boundary is based on 1997 version**

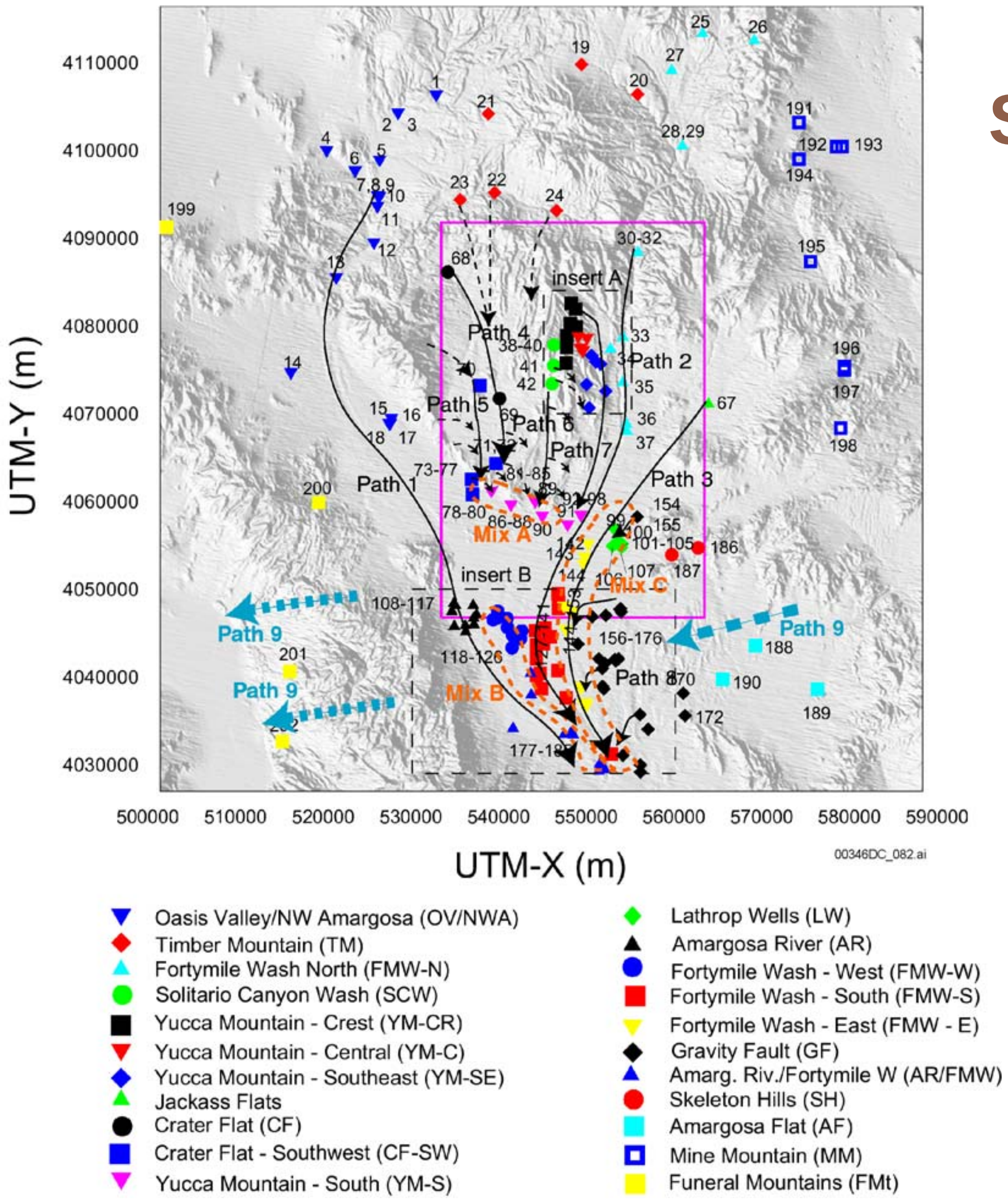
# General Inferred Flow Directions in Death Valley Regional Flow System –

## Central Death Valley Subregion




- General flow direction is southerly from recharge areas in north to discharge areas in south
- In vicinity of Yucca Mountain apparent flow direction is southerly
- Southwesterly flow inferred from Specter Range to Death Valley

# Geochemistry Signatures and Inferred Flow Directions and Mixing in Death Valley Regional Flow System




- Dissolved constituents (chloride, sulfate, delta-deuterium, etc) indicative of common trends
- Water types are grouped by similar geochemical signatures along flow paths
- Mixing zones indicate areas where distinct waters mix in larger flow system

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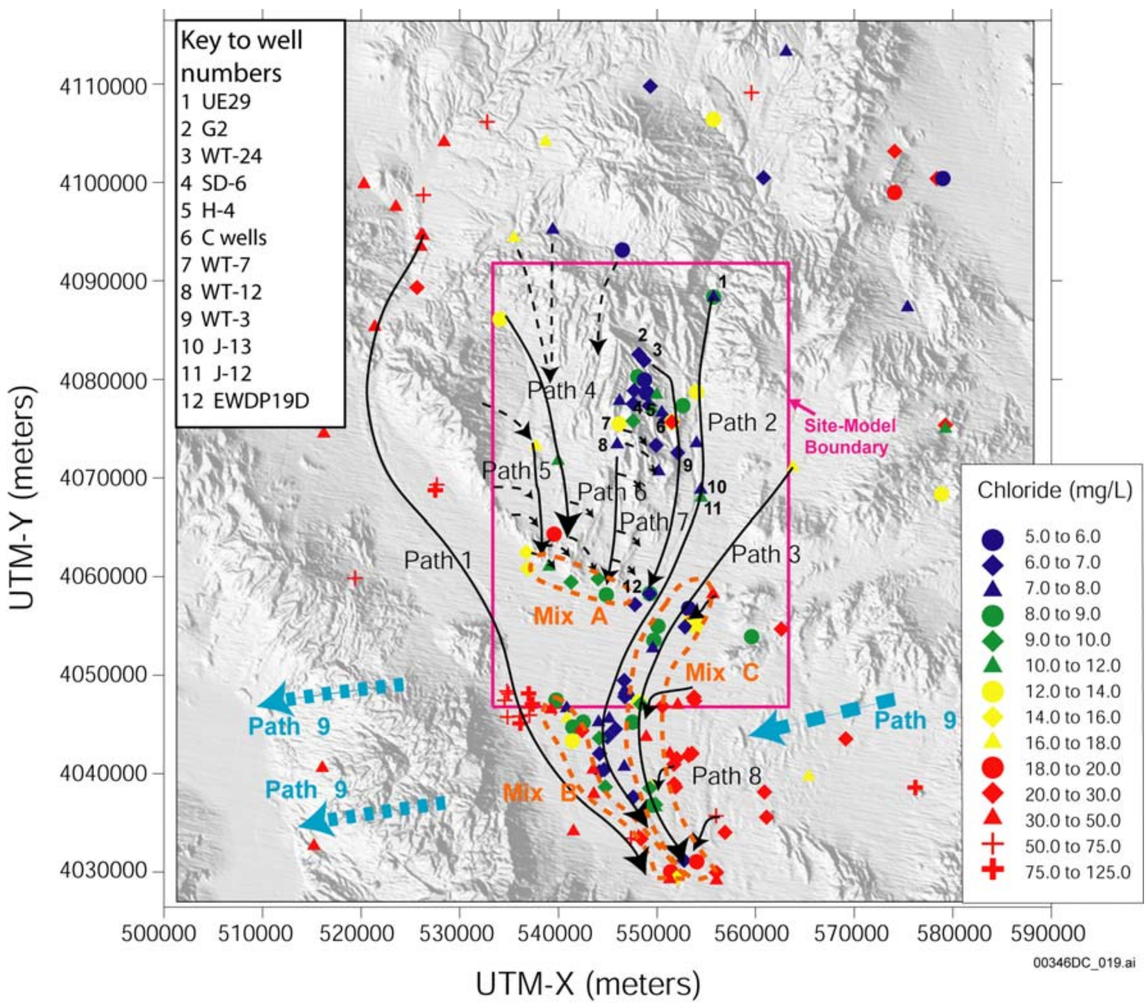
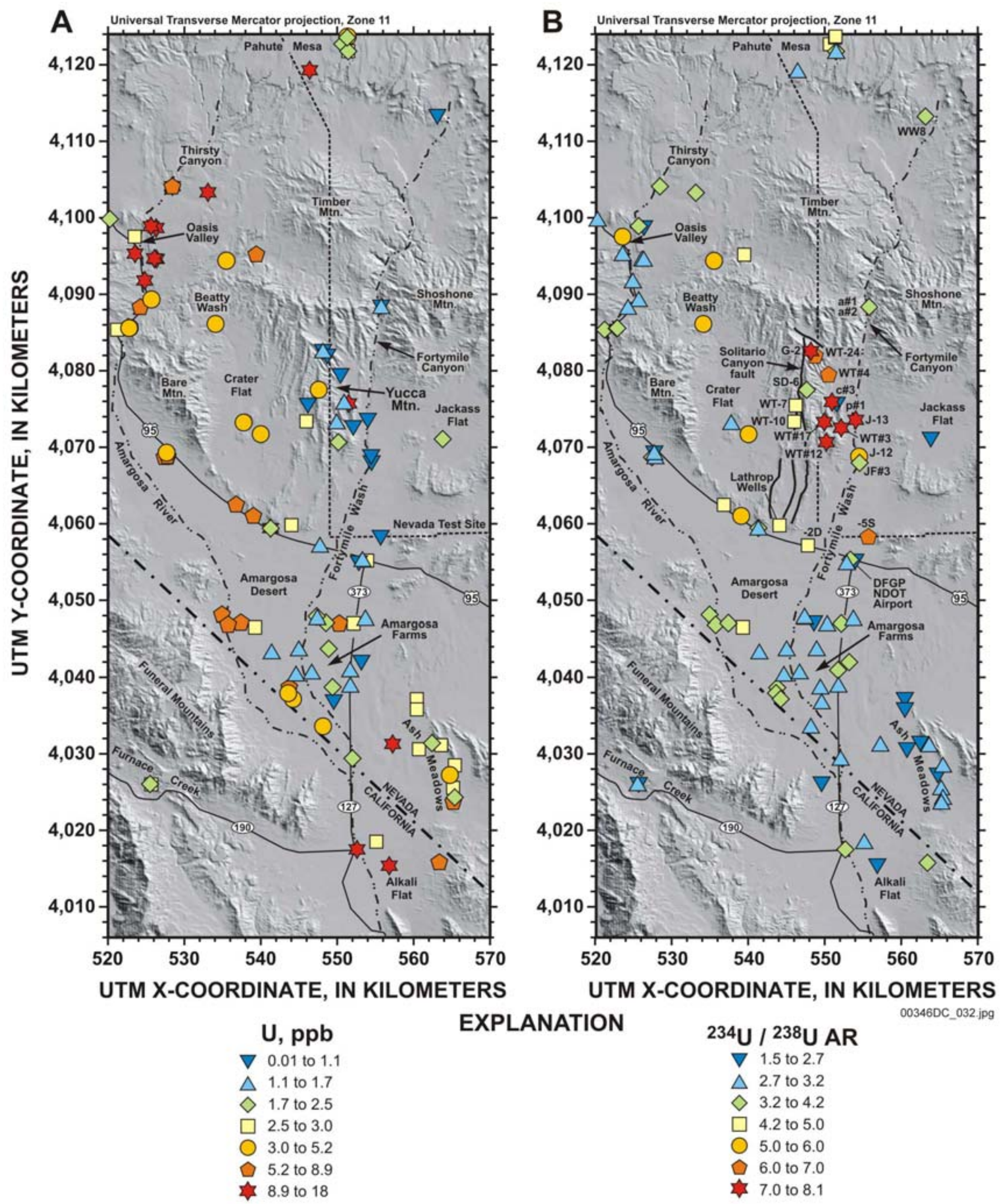
# Geochemical Signatures and Inferred Groundwater Flow Paths – Chloride example




- Chloride concentration generally increases along flow path due to water-rock interactions
- Path 9 represents deep underflow in carbonate aquifer
- Geochemistry in vicinity of Yucca Mountain indicates generally a southerly flow with eastern component across Solitario Canyon fault (Path 7)




# Regional Variation in Uranium and Uranium Isotope Ratios

- **Generally uranium concentrations increase in the direction of groundwater flow**
- **Generally uranium $^{234}U/^{238}U$ isotope ratios are greatest in areas recharged beneath thick unsaturated sections and decrease along the flow path**
- **These data are indicative of a generally southerly groundwater flow direction**

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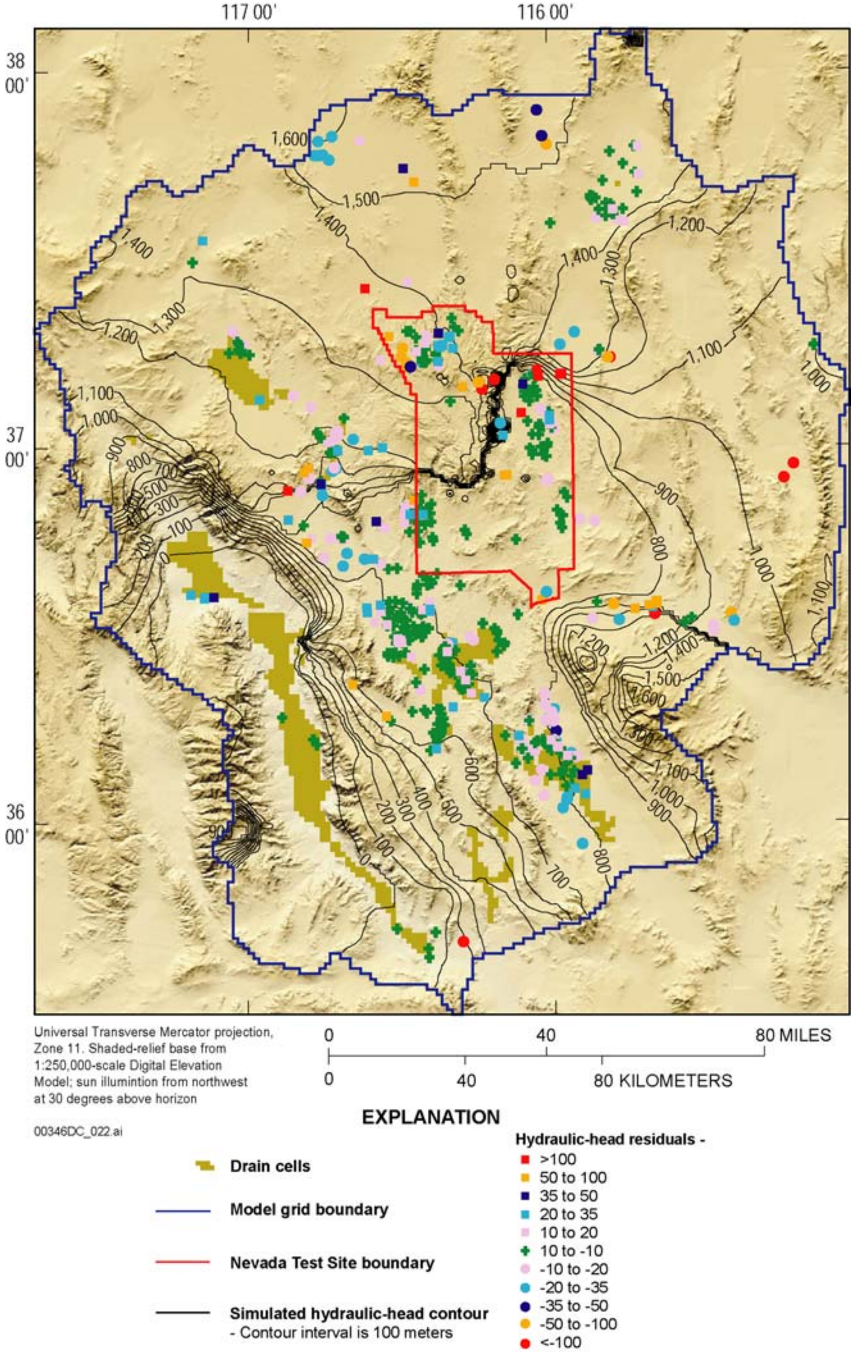
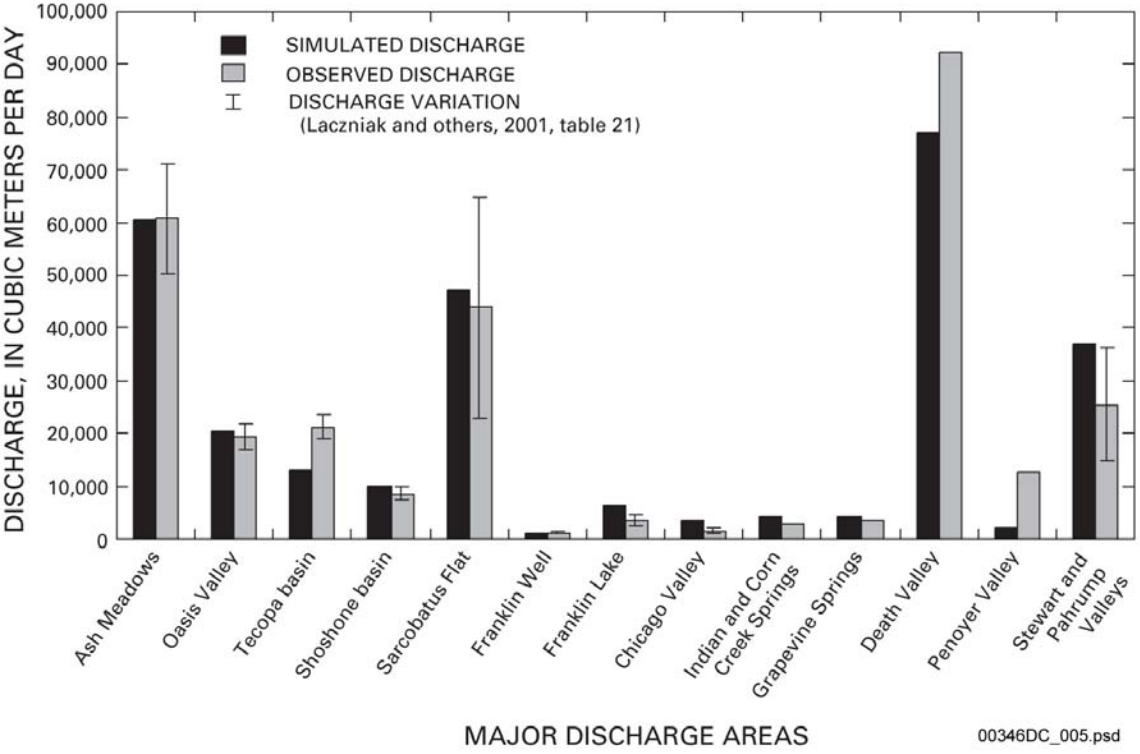
# Groundwater Flow Model of the Death Valley Regional Flow System




- Regional model developed by USGS was updated in D'Agnese et al., 2002
- Updated model included refined hydrogeologic framework model and revised recharge and discharge estimates
- Hydraulic head residuals indicate reasonable agreement in vicinity of Yucca Mountain
- Largest difference are in areas of steeper hydraulic gradients or areas with limited observations

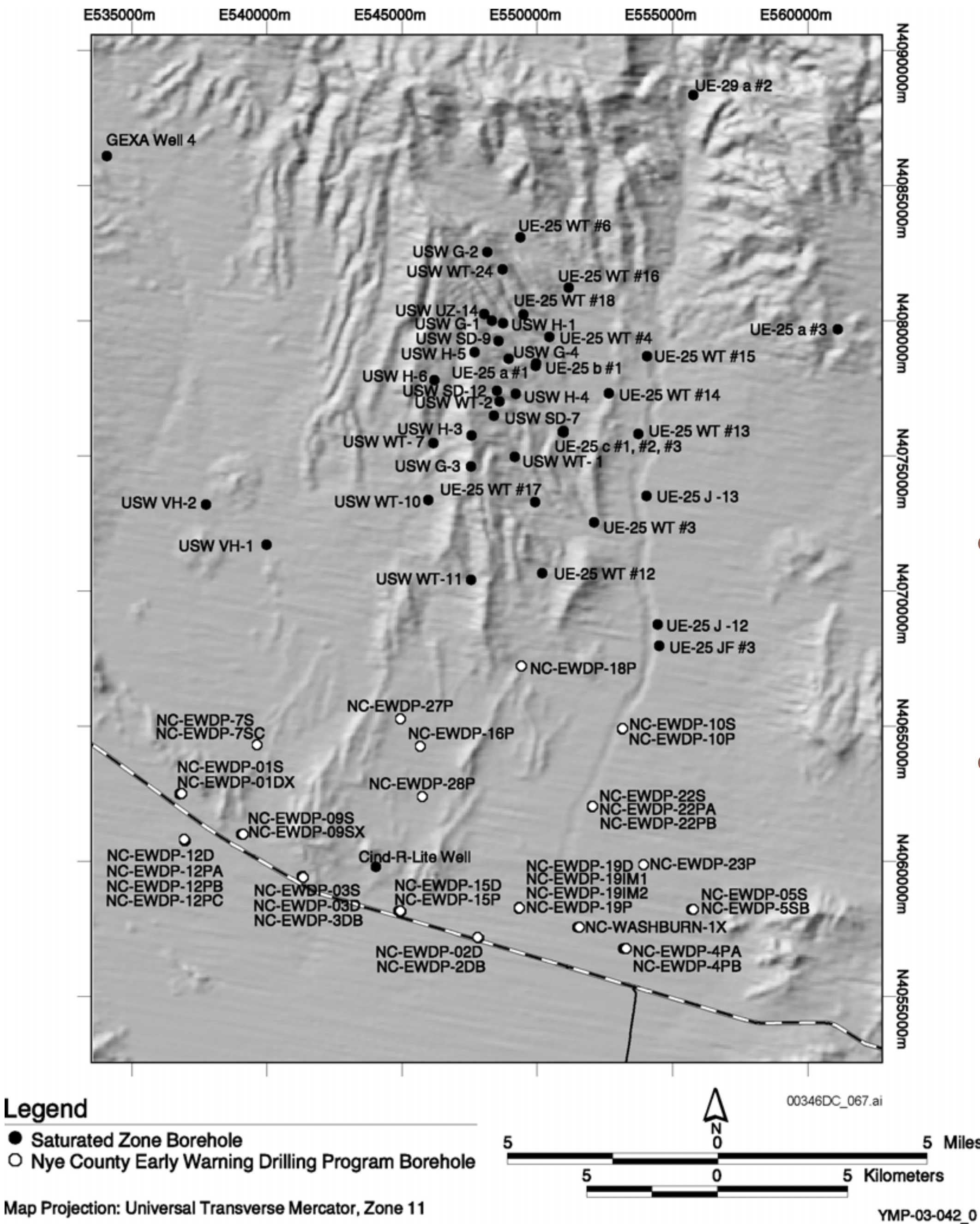
# Comparison of Inferred and Simulated Groundwater Discharge in Regional Flow Model




- Regional discharge estimates compare well to regional model predictions
- Comparison of regional recharge and discharge helps constrain the water budget in the Death Valley region

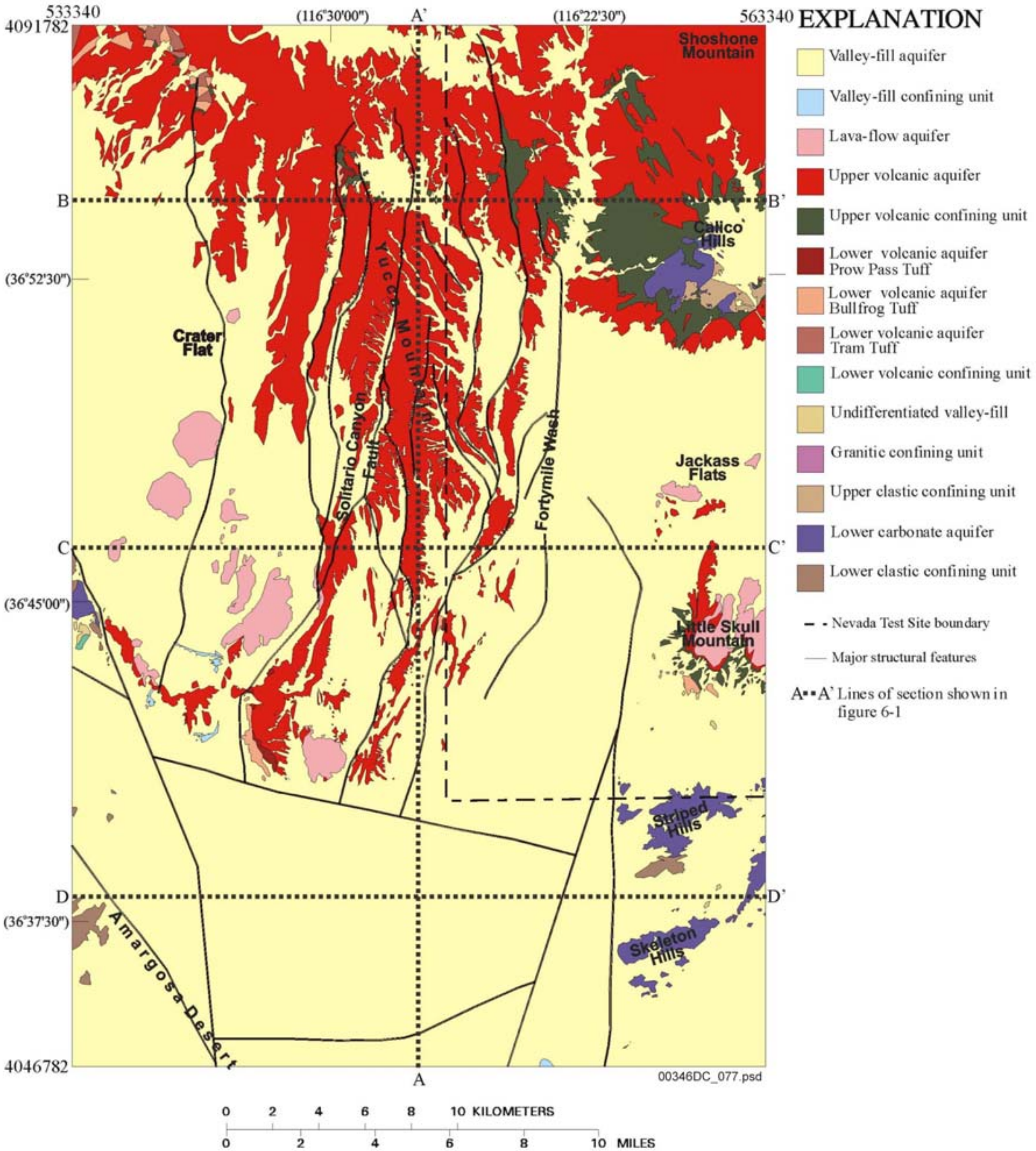
# Site-Scale Groundwater Flow Model

- **Regional model allows definition of general flow directions and provides contraints on volumetric flow rates through aquifers**
- **Site-scale model provides greater detail of flow directions and flow rates through different hydrogeologic units of relevance to repository performance**
- **Site-scale model builds on observations of hydraulic heads and permeability in DOE and Nye County boreholes and discrete large scale aquifer tests conducted in the C-wells complex and the Alluvial Testing Complex**




# Boreholes used in the Development of the Site-Scale Groundwater Flow Model

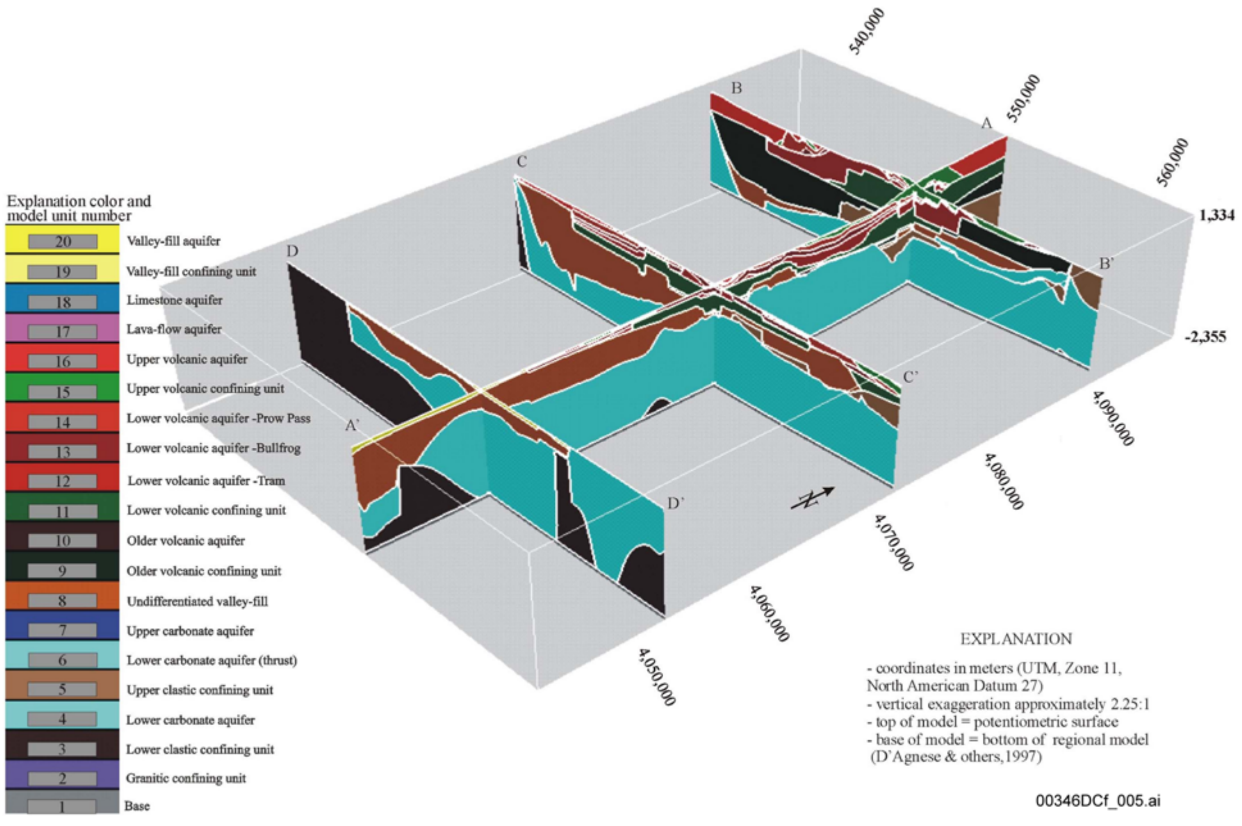
- DOE and Nye County boreholes used to develop parameters and measure hydraulic head
- Borehole coverage significantly expanded by Nye County-DOE cooperative drilling program (especially in alluvium and in vicinity of alluvium-tuff contact)



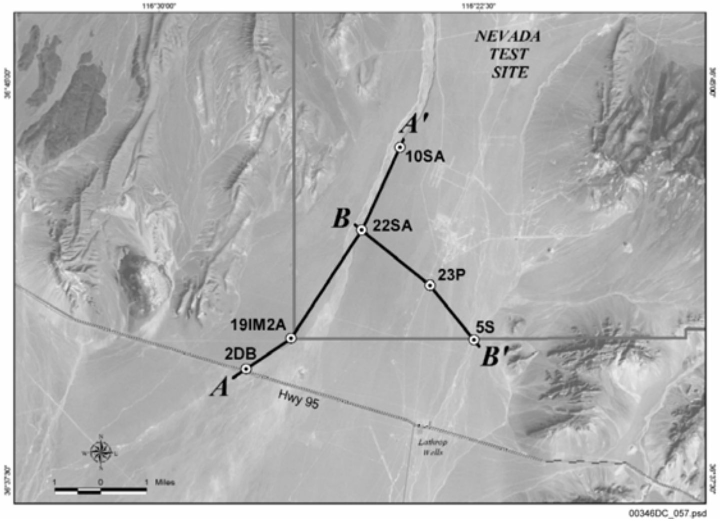

# Site-Scale Geologic Representation – Geologic Unit Outcrops

- **Geology in saturated zone consists of continuation of strata identified in unsaturated zone**
- **Lateral continuity of tuff aquifers is limited due to offset along N-S trending faults**

# Site Scale Geologic Representation – Hydrogeologic Cross Sections

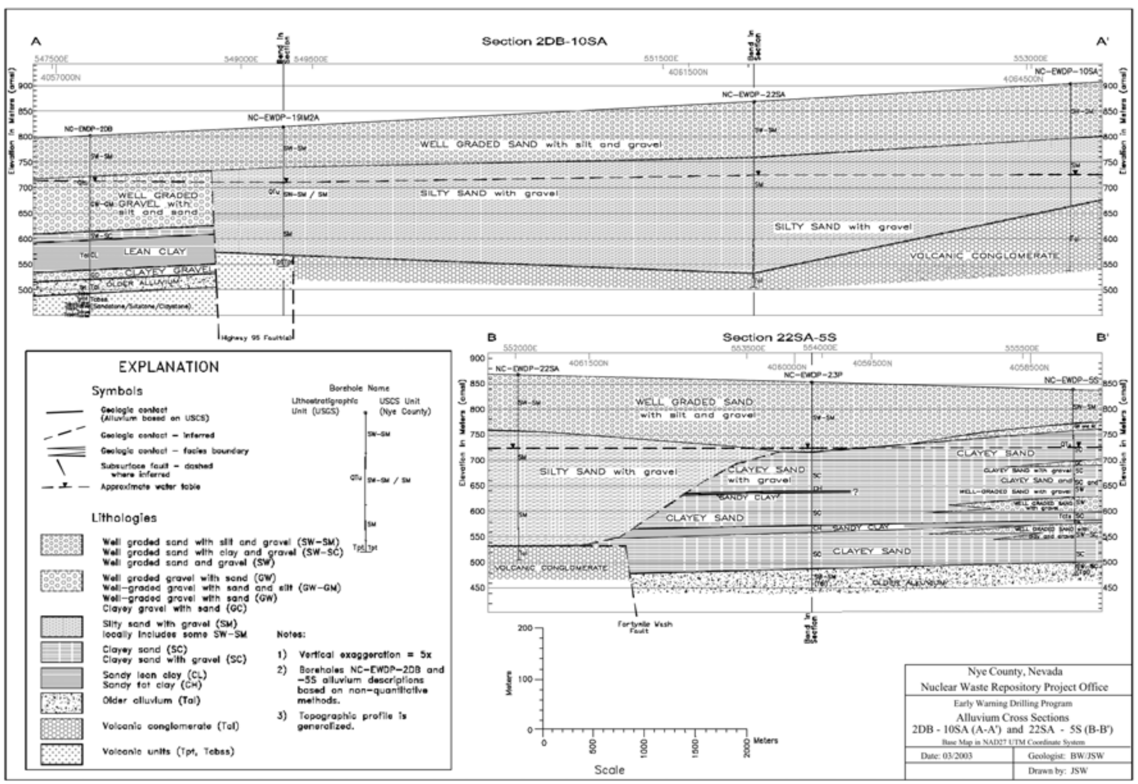



- 20 discrete layers used to define hydro-stratigraphy of the site scale groundwater flow model
- Total vertical extent about 3000 meters




# Extent of Alluvium Identified in Nye County Boreholes

- **Nye County boreholes drilled along U.S. 95 and northward toward Yucca Mountain**




NOTES: USCS = Unified Soil Classification System; USGS = U.S. Geological Survey

- **Nye County borehole information available on their web site - www.nyecounty.gov**

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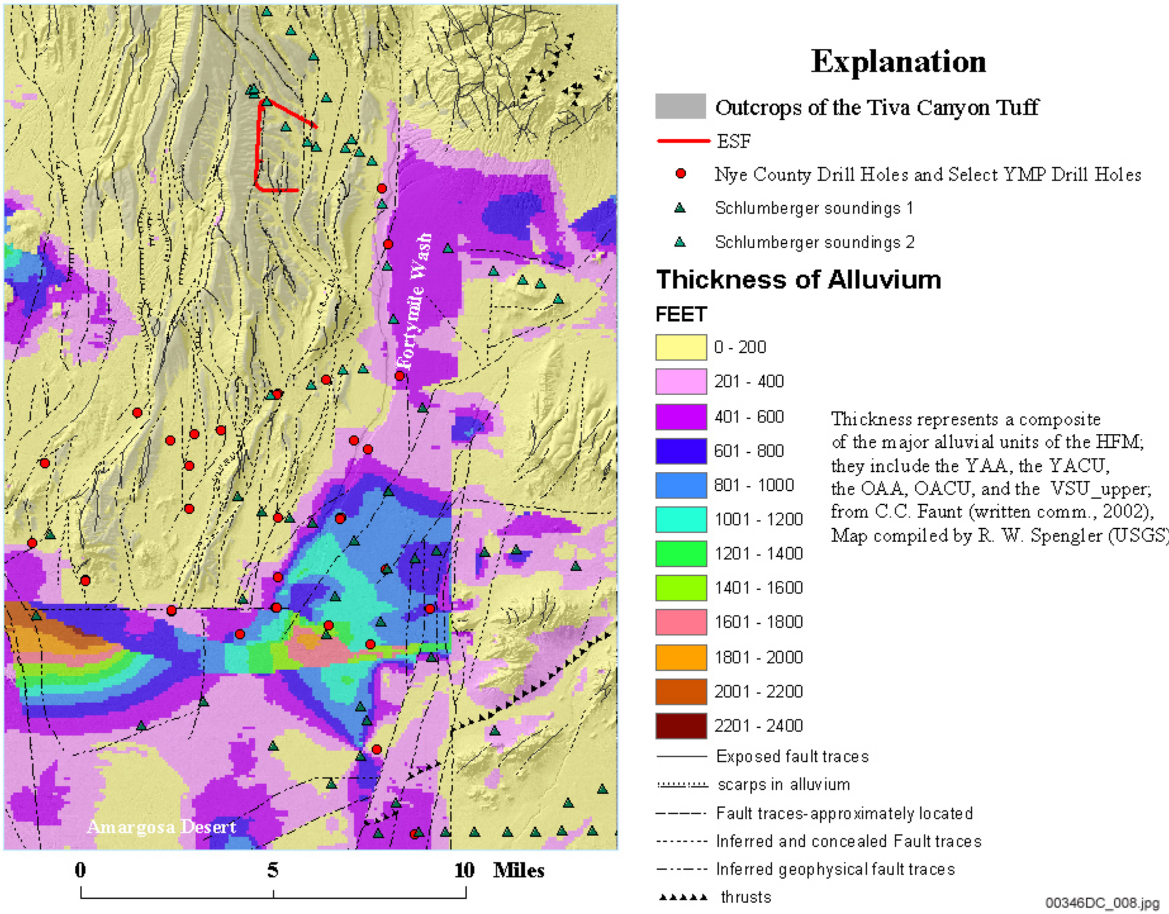
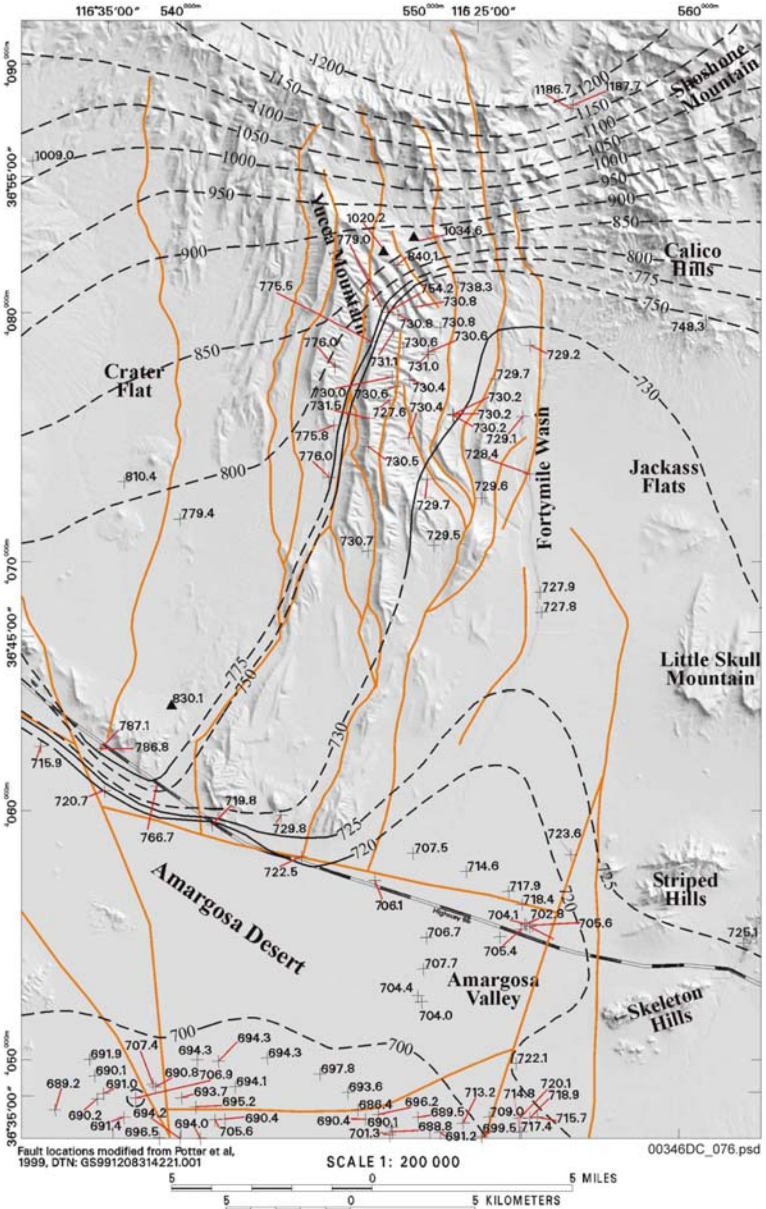
# Extent of Alluvium Identified in Nye County Boreholes and Geophysics




- **Alluvium thickness varies over the site**
- **Generally alluvium is thickest under Fortymile Wash (about 800 ft) and southward towards Amargosa Valley**
- **This information used to constrain location of tuff-alluvium contact**




Potentiometric-Surface Map,
Assuming Perched Conditions North of Yucca Mountain,
in the Saturated Site-Scale Model Area

—700— Potentiometric contour - Shows altitude of potentiometric surface. Contour interval, in meters, is variable and dashed where approximately located. Datum is sea level

Tertiary fault

+ 713.2 Well - Number is potentiometric altitude, in meters. Datum is sea level

▲ 830.1 Well - Number is potentiometric altitude, in meters, which is assumed to represent perched conditions. Datum is sea level

# Site-Scale Potentiometric Surface

- Representation considers heads at USW G-2 and UE-25 WT#6 to be locally perched
- Assuming isotropic permeability, this potential surface indicates generally southeasterly flow from Yucca Mountain and then southerly flow under Fortymile Wash

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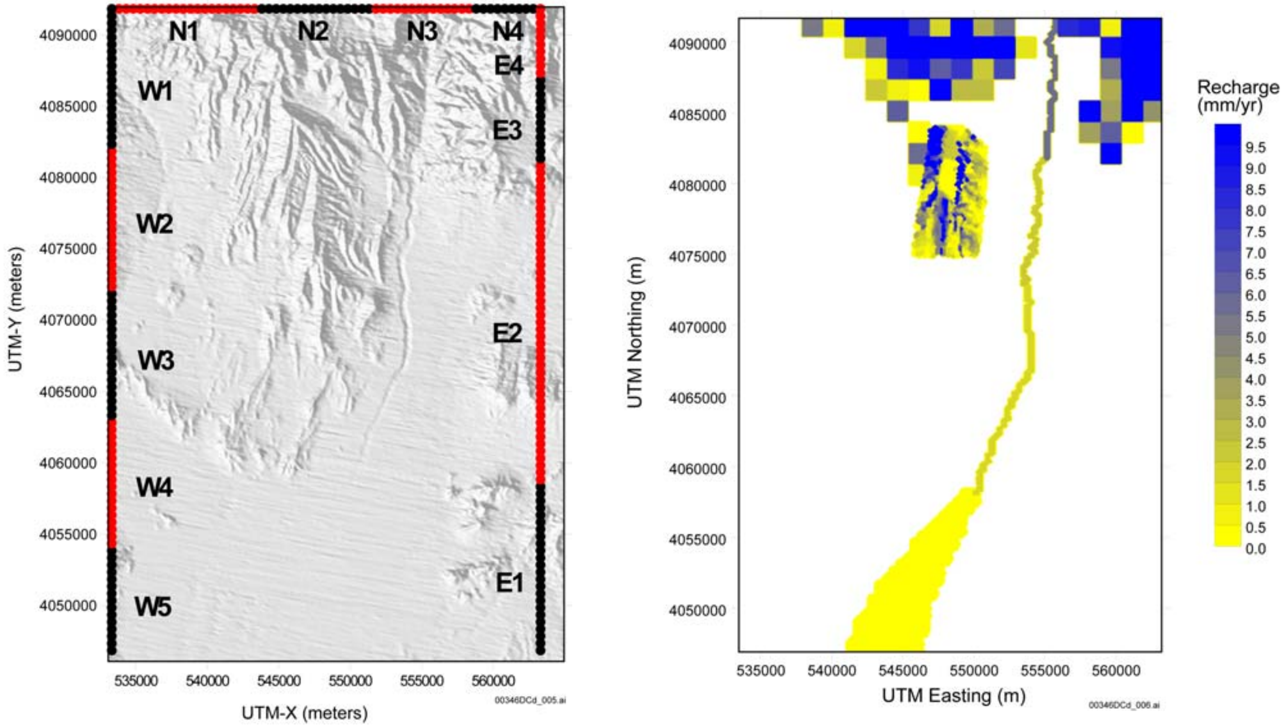
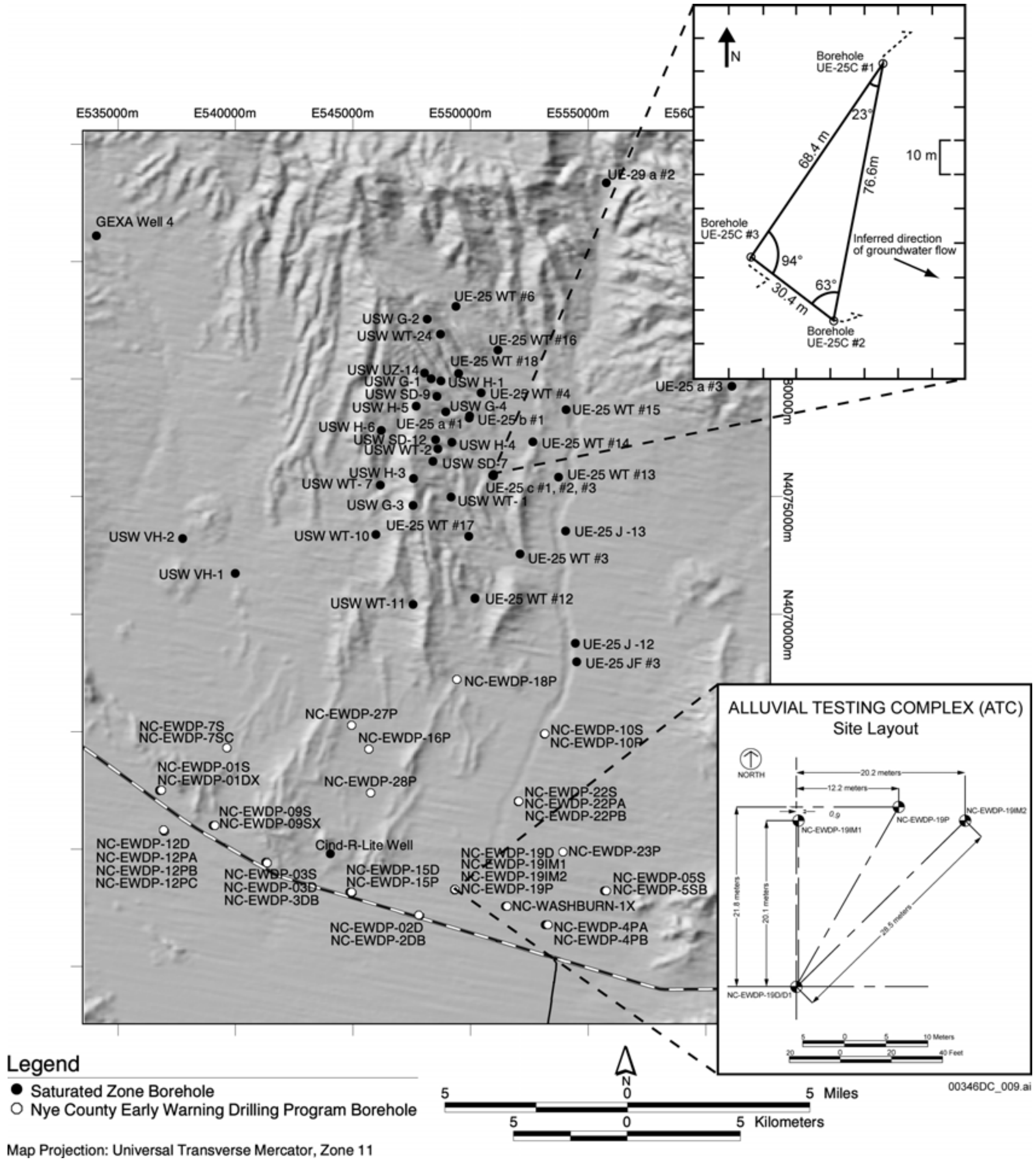
# Site Scale Boundary Fluxes Compared to Regional Model Fluxes




| Boundary | Regional Model | Site-Scale Model (million $m^3$/yr) |
|---|---|---|
| North | - 6.1 | - 5.4 |
| East | - 17.7 | - 16.4 |
| West | - 3.7 | - 0.1 |
| South | 28.9 | 22.8 |

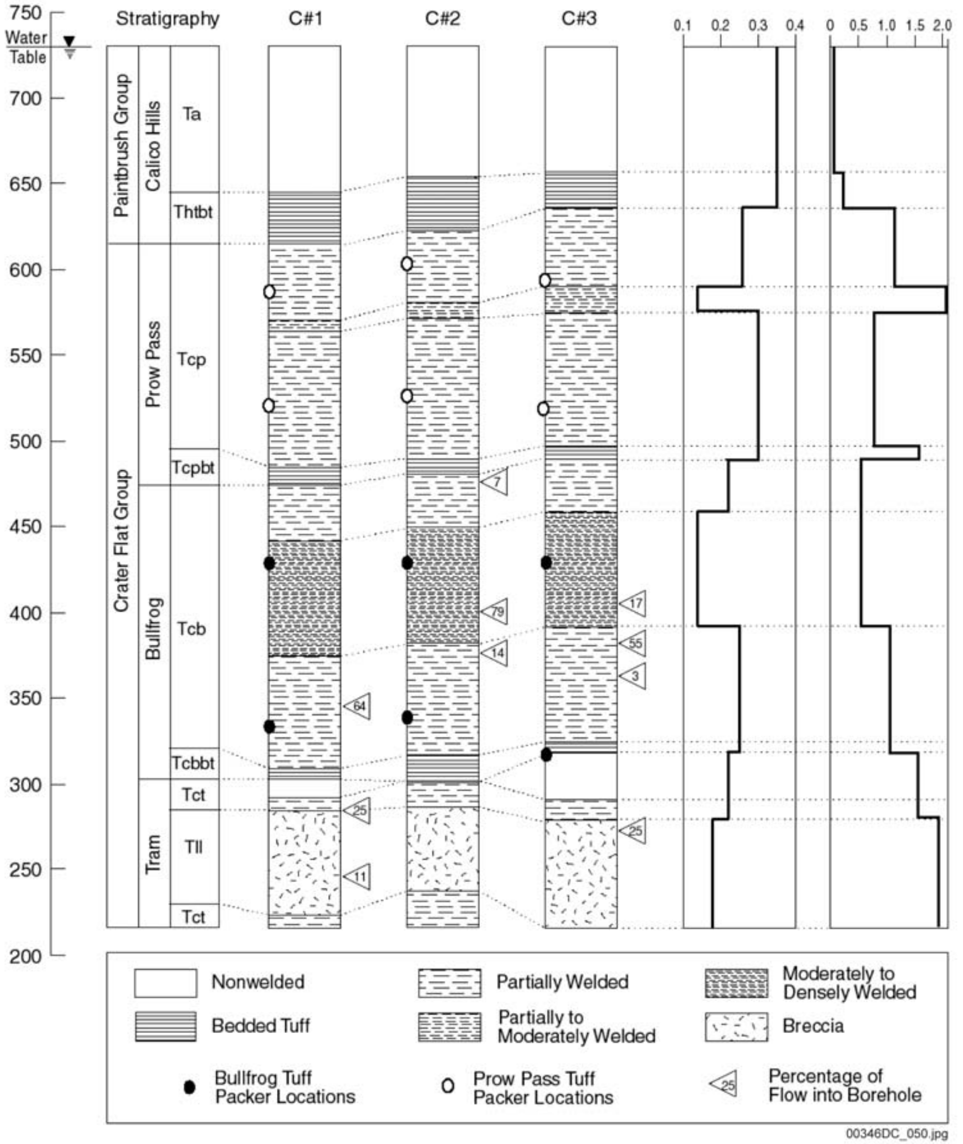
**NOTE: Negative values represent lateral inflow, positive values represent outflow.**
**Regional model provides pre calibration targets for site scale results.**




# Location of C-Wells and Alluvial Testing Complexes

- Detailed hydrogeologic and tracer tests conducted in tuff aquifers at C-wells and in alluvial aquifer at ATC
- Spacing of wells (tens of meters) determined from desire to develop flow recirculation cells for tracer tests
- Long duration pump test at C-wells stressed wells several kilometers away

# C-Wells Stratigraphy and Hydraulic Characteristics



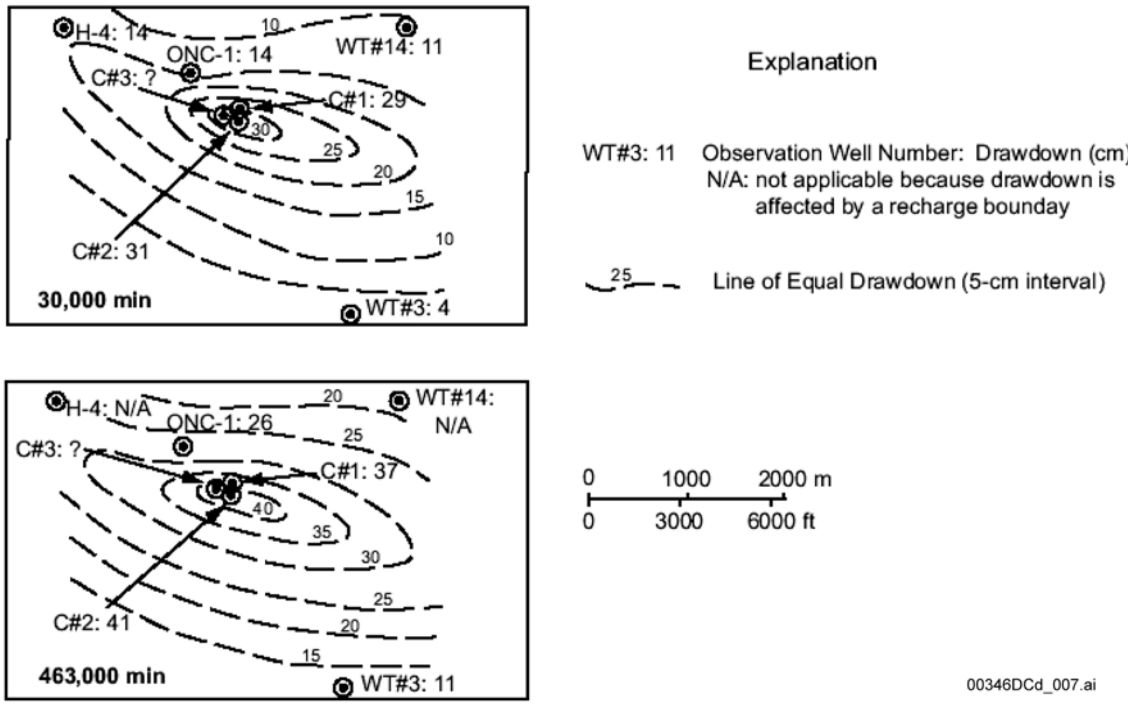

Source: Information derived from Geldon (1993 [101045, WRIR 92-4016 (pp. 35-37, 68-70). Packer locations from Scientific Notebook SN-USGS-SCI-036 [162854], [162856], [162857], [162858].

NOTE: Packer locations indicate intervals in which tracer tests described in this report were conducted. (note that the tracer tests were conducted between UE-25 c#2 and c#3).

- **Fluid logging indicated that only small portion of borehole was providing most of flow (with spacing of several ten's of meters)**
- **Tracer tests conducted in both Prow Pass and Bullfrog units**

**NOTE: Well logs represent matrix porosity (left) and fracture spacing (fractures/m) (right)**

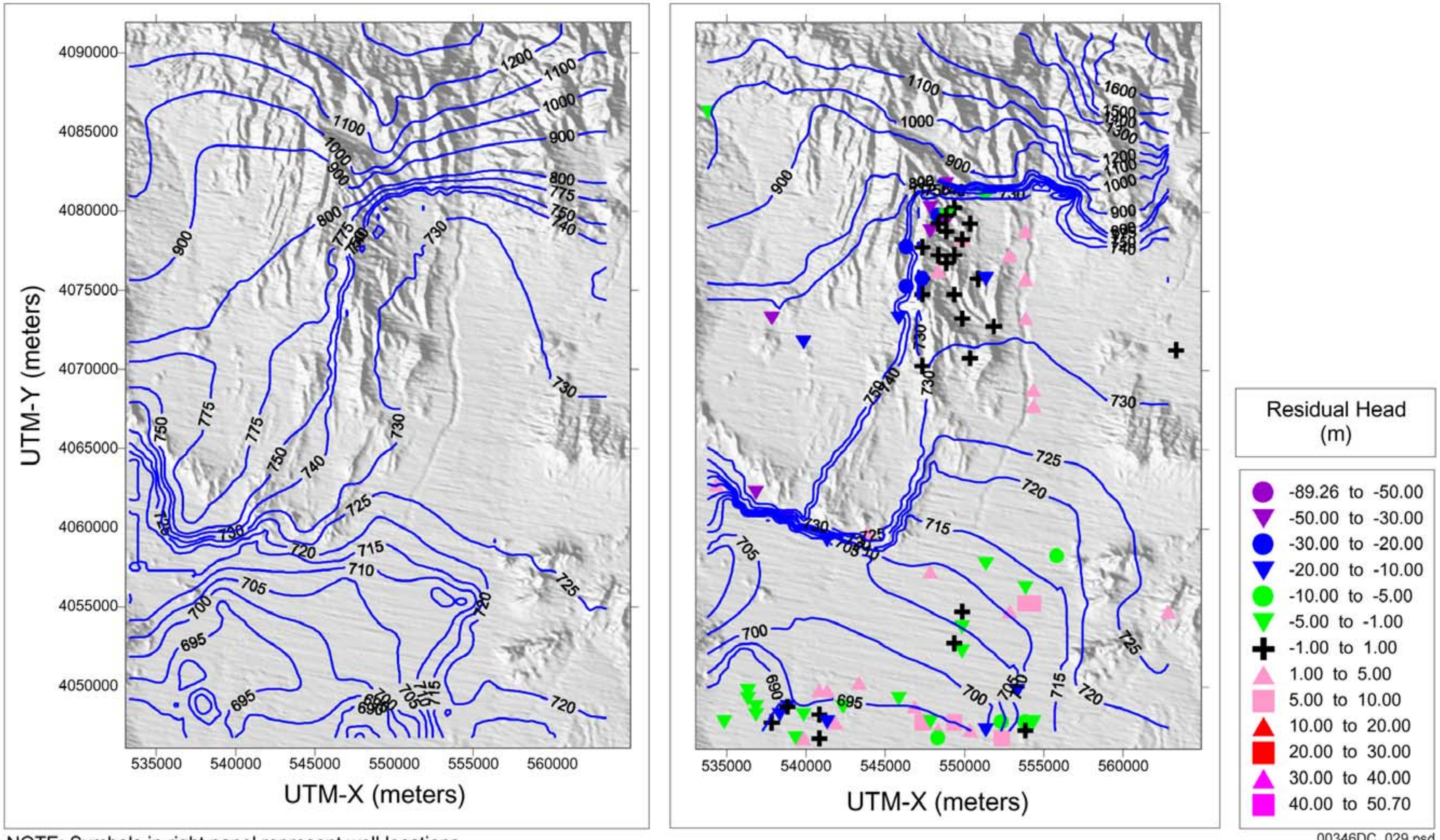
# C-Wells Long Term Pump Test




**30,000 minutes = 21 days**
**463,000 minutes = 321 days**

- **C-wells pumped at ~ 800 m$^3$/day from May 1996 to November 1997 (total 0.44 million m$^3$)**
- **Drawdowns observed over 2 km away**
- **Drawdowns interpreted to develop large scale estimates of transmissivity and anisotropy**

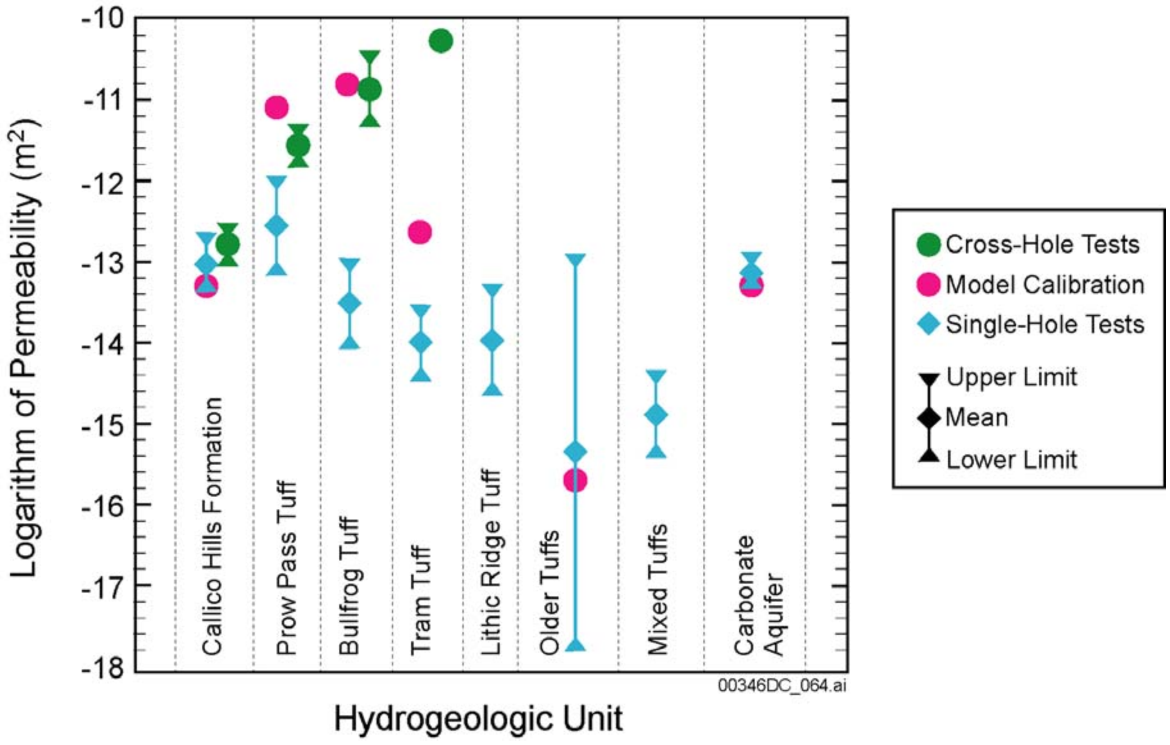
# Site Scale Modeled and Observed Potentiometric Surfaces



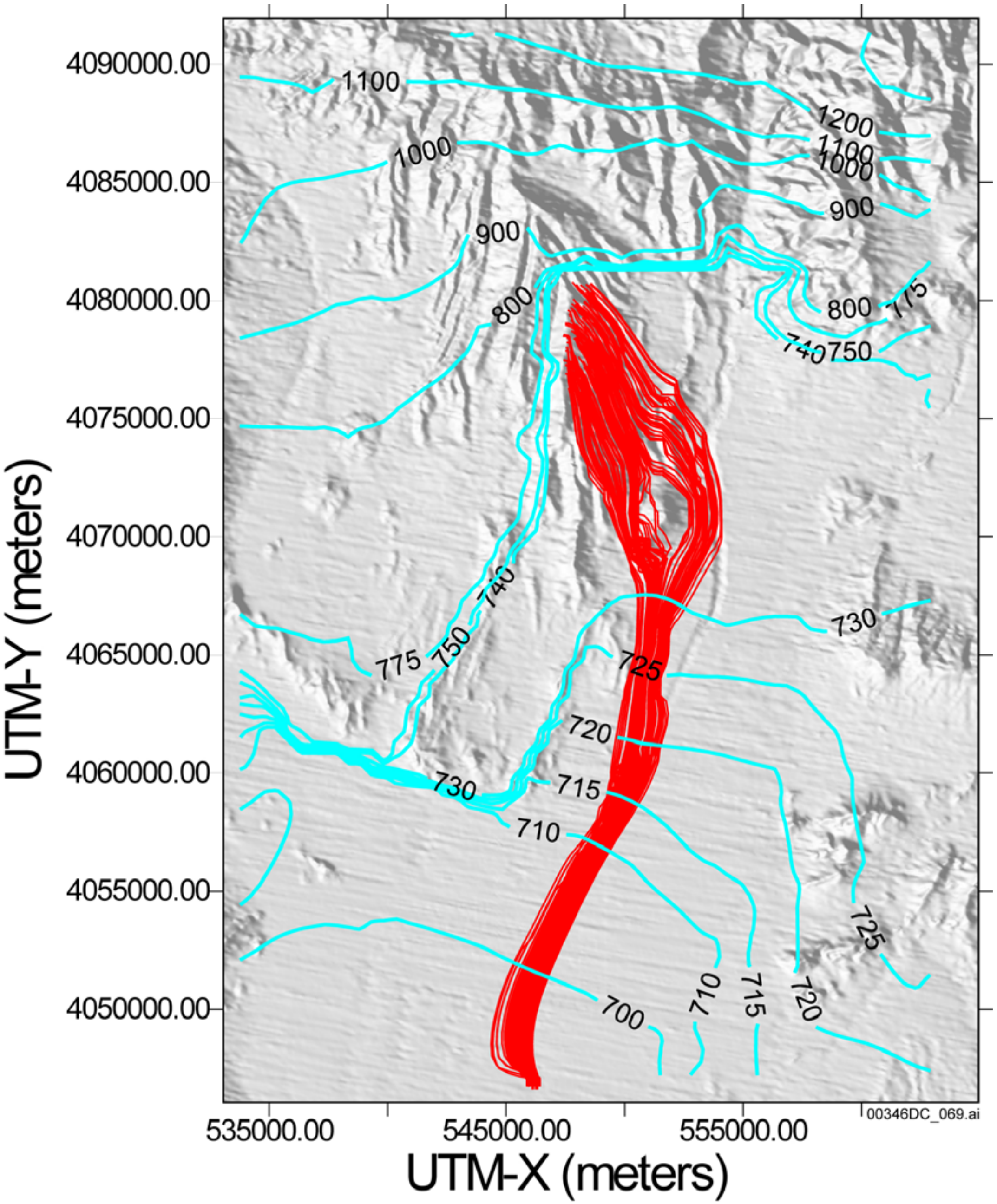

NOTE: Symbols in right panel represent well locations.

- **Observed (left) and predicted (right) heads agree with greatest differences in areas of steep hydraulic gradients**

# Site-Scale Modeled and Observed Permeability Values

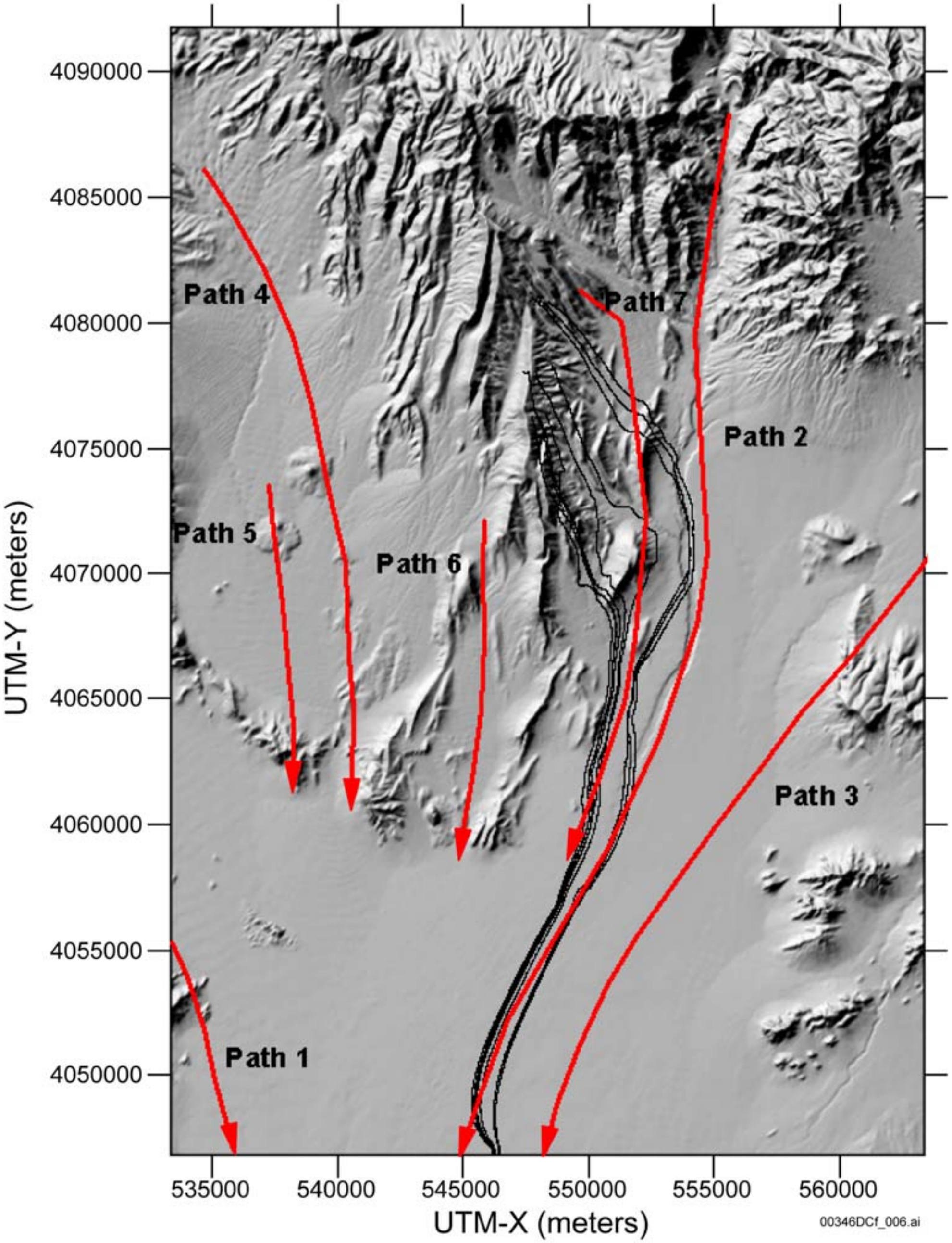



- Generally cross holes tests intersect larger rock mass and are more indicative of in situ conditions
- Single cross hole test in Tram Tuff is believed more indicative of fault near test
- Reasonable match achieved



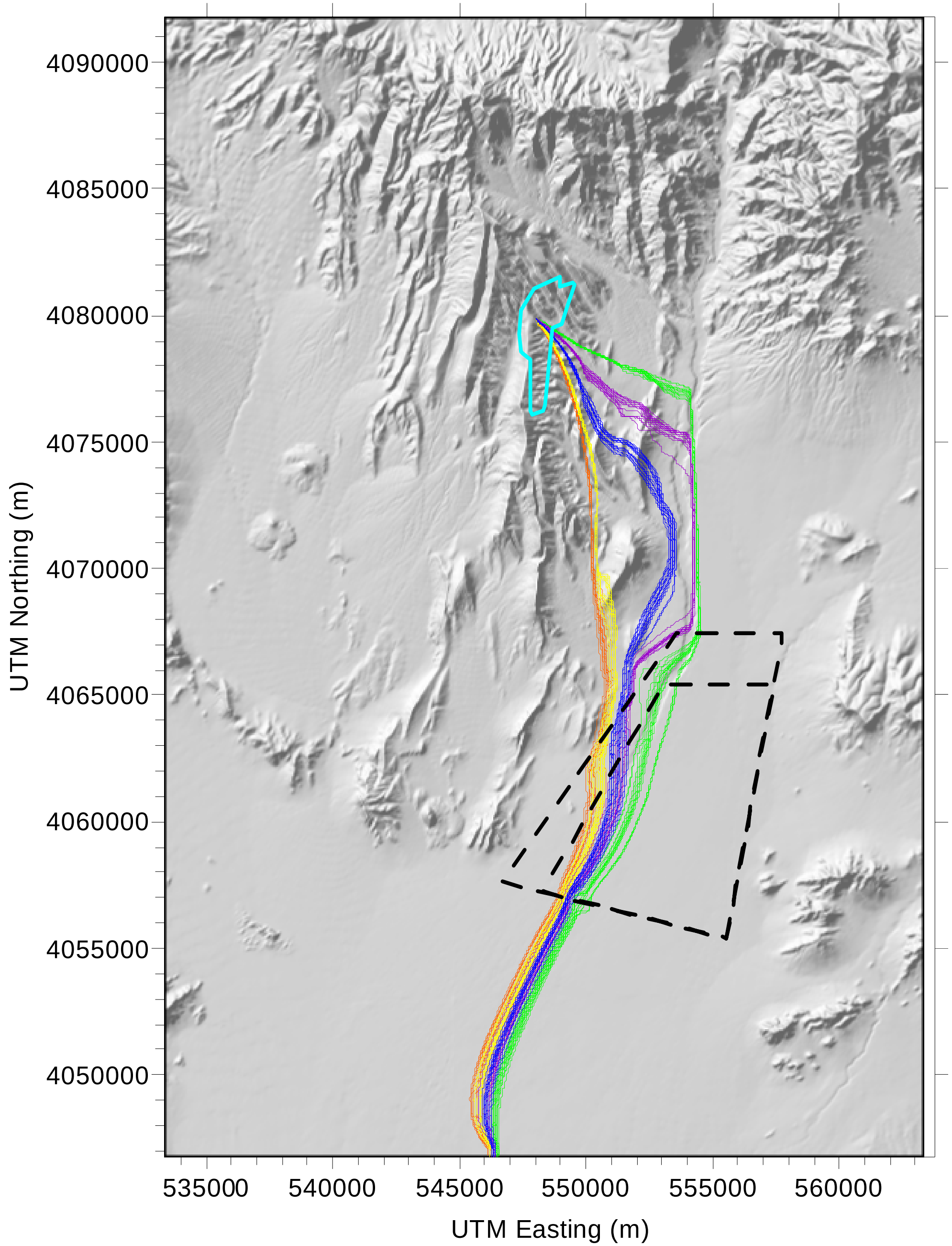

# Calculated Site Scale Groundwater Flow Paths

- **Nominal flow path trajectory is generally southeasterly from Yucca Mountain**
- **Flow beneath Fortymile Wash is south-southwesterly**
- **Uncertainty in flow paths due to anisotropy and uncertainty in boundary conditions**
- **Flow rates of about 0.7 m/yr under Yucca Mountain increasing to about 2.3 m/yr at 18 km**




# Comparison of Calculated Flow Paths with Geochemistry Inferred Flow Paths

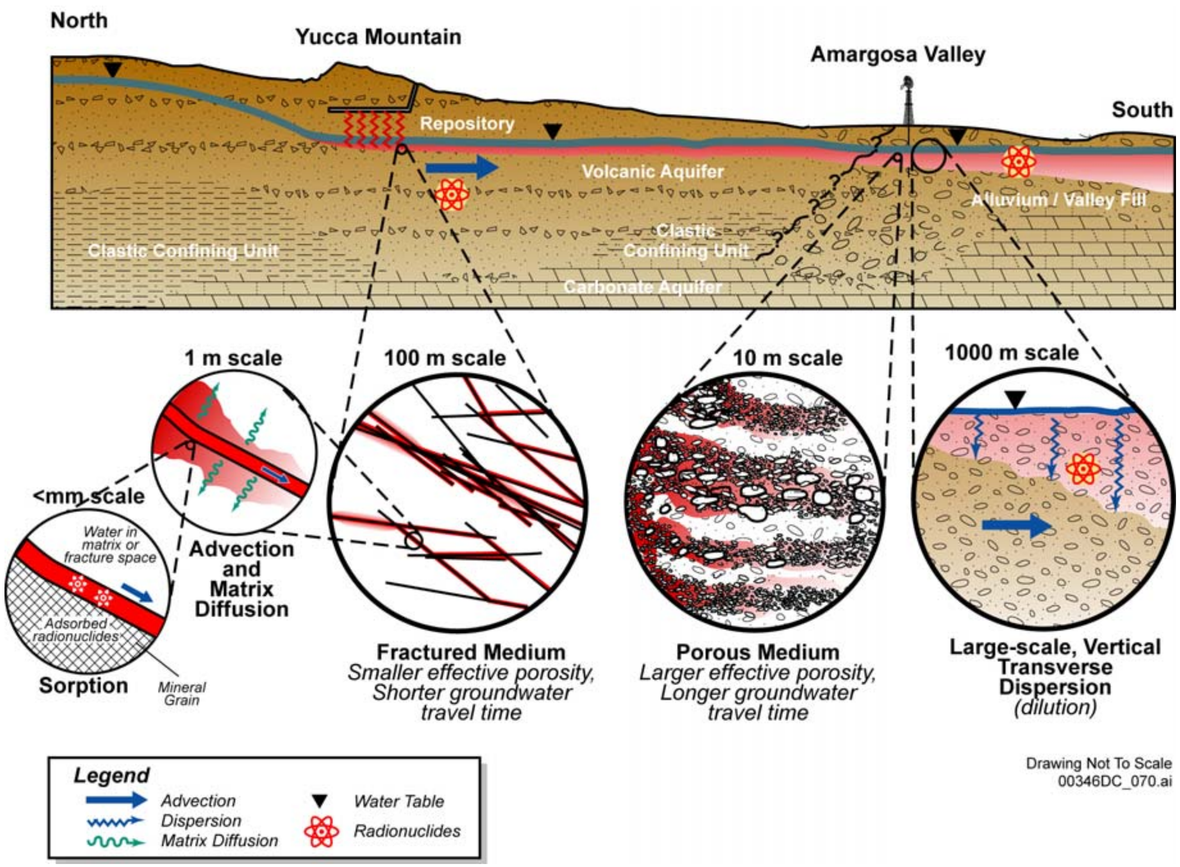
- **Calculated flow paths follow geochemically inferred paths 2 and 7**
  - **southeasterly flow to axis of Fortymile Wash and then along axis of Fortymile Wash**




# Uncertainty in Flow Paths Lengths in Alluvium

- Uncertainty in flow path a function of uncertainty in anisotropy in tuff aquifers
  - green: 0.05
  - blue: 1.0
  - red: 20
- Uncertainty in alluvium contact indicated by dashed lines
- Flow path length in alluvium to point of compliance ranges from 1 to 10 km

# Radionuclide Transport Processes

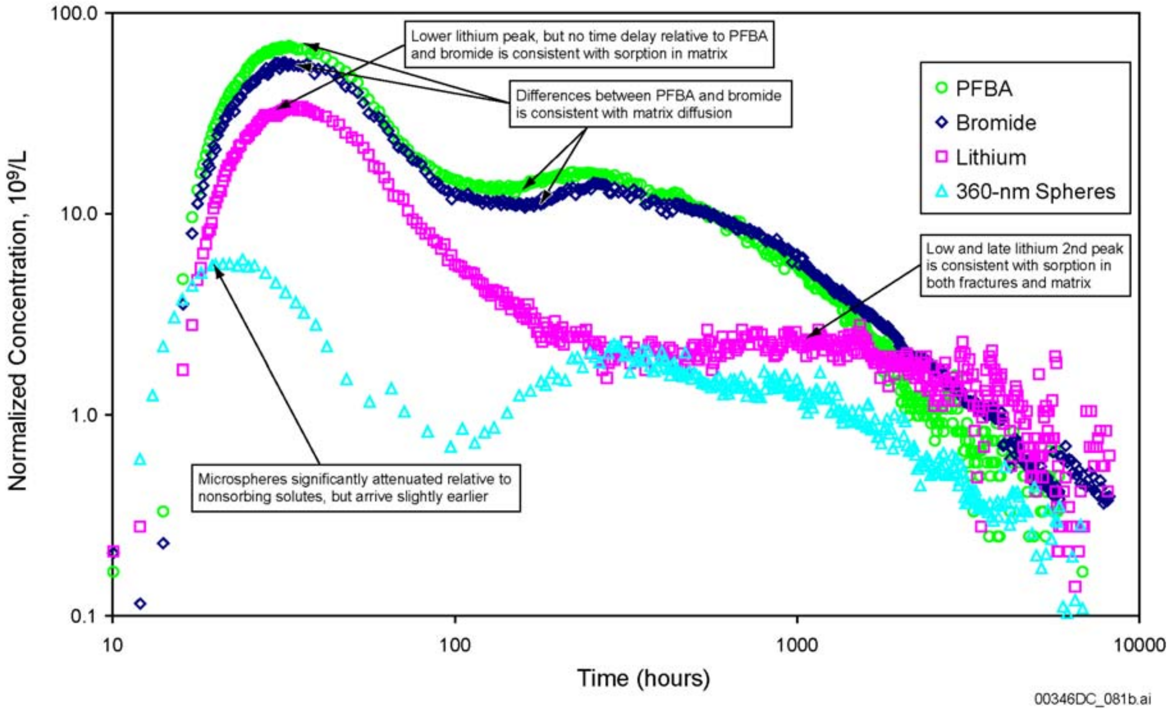



- Transport processes include advection, dispersion, matrix diffusion and retardation
- Advection occurs primarily through fractures in tuff aquifers and through matrix in alluvial aquifer
- Transport characteristics differ between tuff and alluvium

# Site Scale Radionuclide Transport

- **Groundwater flow models provide projections of flow paths and flow rates**
- **Transport model provide projections of flow velocities and radionuclide transport times between the point radionuclides enter the saturated zone to the point they are withdrawn from the well used by the hypothetical person**
- **Although transport model also project the spatial variation in concentration along the flow path, this information is not used due to the conservative assumption that all the activity is captured by the well**
  - **therefore only activity flux is required**
  - **concentration of water in well (in Ci/$m^3$) = activity flux (in Ci/yr) divided by the annual water demand (3.7 million $m^3$/yr)**

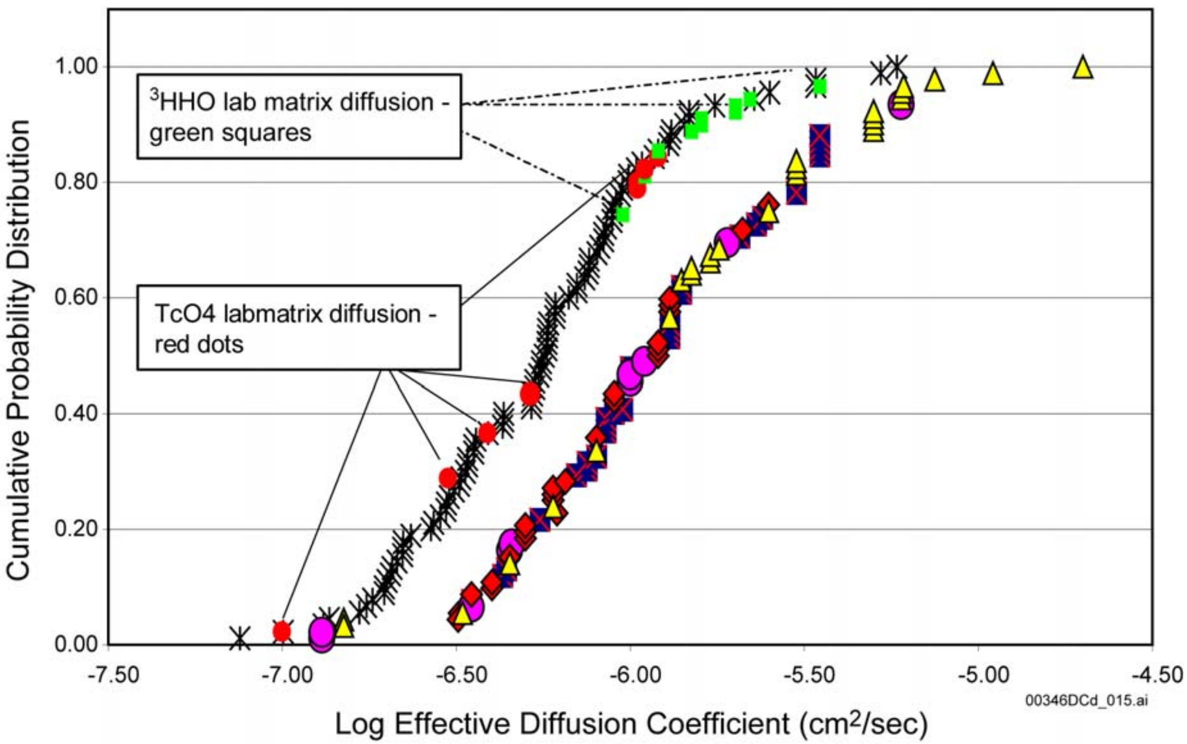
# C-Wells Transport Test Data




PFBA - Pentafluorobenzoic Acid

- **Tracer tests confirm dual continuum (fracture - matrix) transport model**
- **Matrix diffusion model confirmed (Bromide larger diameter than PFBA)**
- **Sorbing tracers (e.g., Lithium) behave analogously to lab sorption measurements**
- **Colloid mobility confirmed using microsphere analogs**

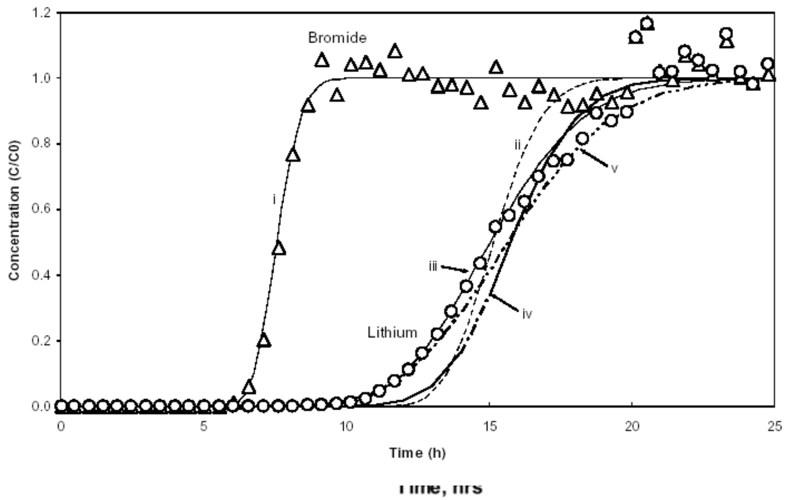
# Matrix Diffusion Coefficient Evaluated in Lab and Field Experiments

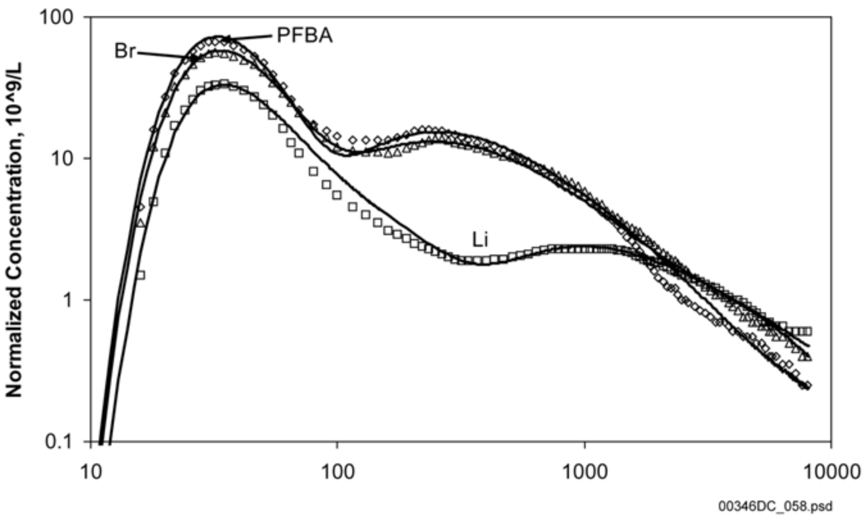



- **Matrix diffusion constrained between $10^{-7}$ and $10^{-5}$ $cm^2$/sec**
- **Lab and field data show similar trends**

Left hand curve represents linear relationship based on porosity and permeability and Rundberg et al, 1987 and Triay 1993 data. Right hand curve represents lab and field data (Reimus et al., 2002): Squares $^3$HHO lab data, diamonds $TCO_4$ lab data, circles $Br^-$ and PFBA field data.

# Comparison of Lithium Transport in Laboratory and Field Tests

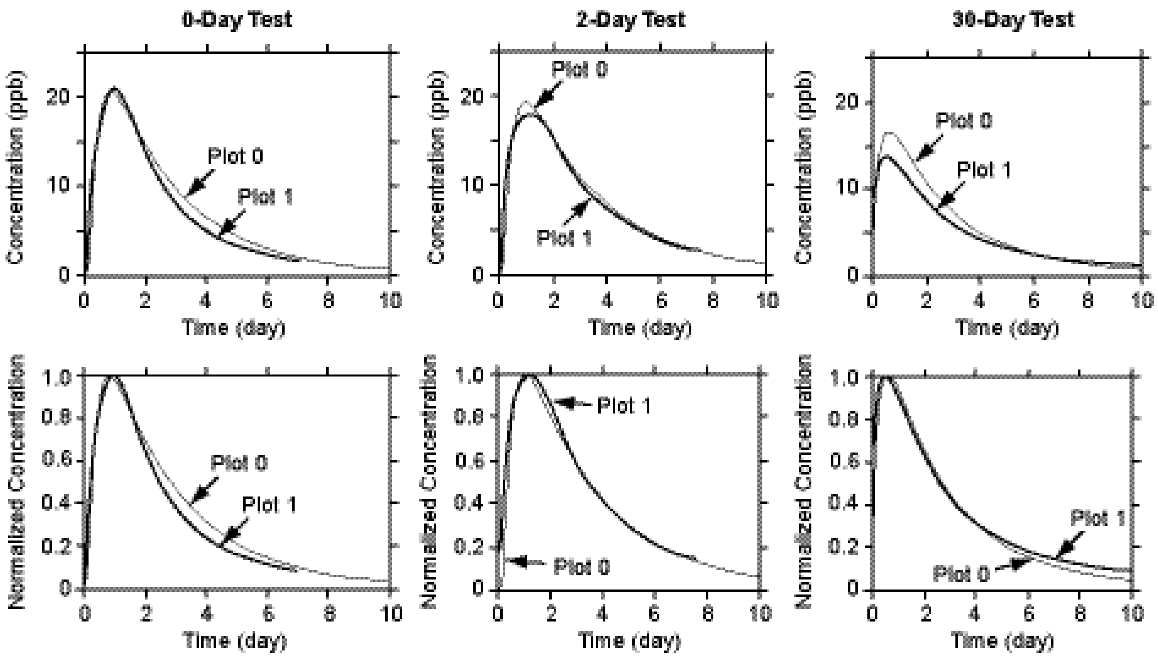



DTN: LA0007PR831231.001 (data). Output DTN: LA0303PR831231.003 (model).

- Laboratory (top figure) and field (bottom figure) Lithium retardation coefficients are similar
- Field $K_d$ (range from 0.6 to 4.1 ml/g) are slightly larger than laboratory $K_d$ (range from 0.1 to 0.3 ml/g)
  - difference perhaps a result of alteration minerals (e.g., clays) removed during preparation of lab samples
- Using laboratory-derived $K_d$ is conservative for post closure performance assessment

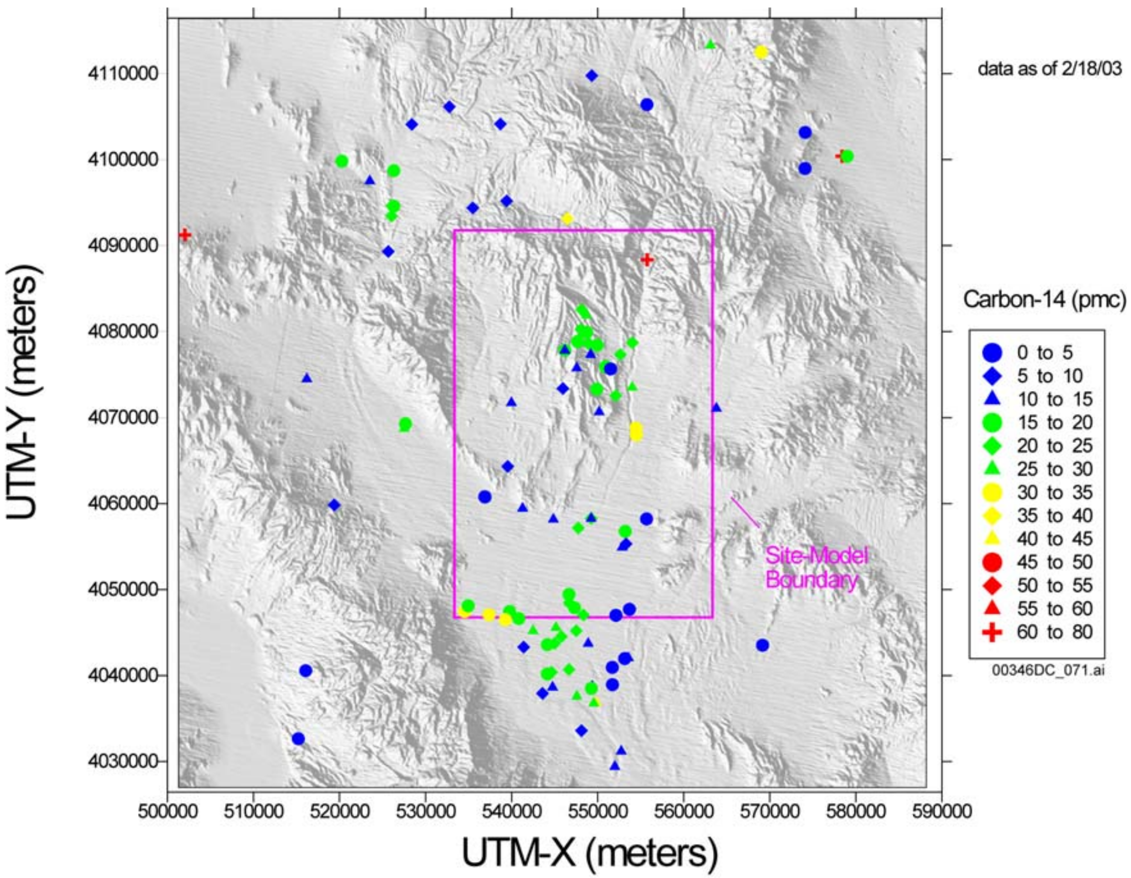
# Single Hole Tracer Test at Alluvial Testing Complex




The plots are fits of three injection-pumpback tracer tests with theoretical curves that result from three solutions to the advection-dispersion equation for the three phases of injection, drift, and pumpback. "Plot 0" is the model fit and "Plot 1" is the data curve. The parameters used in the calculations are: flow porosity = 0.1, natural gradient = 0.002 m/m, *T* for gradient = 20.0 $m^2$/d, specific discharge = 1.5 m/yr.

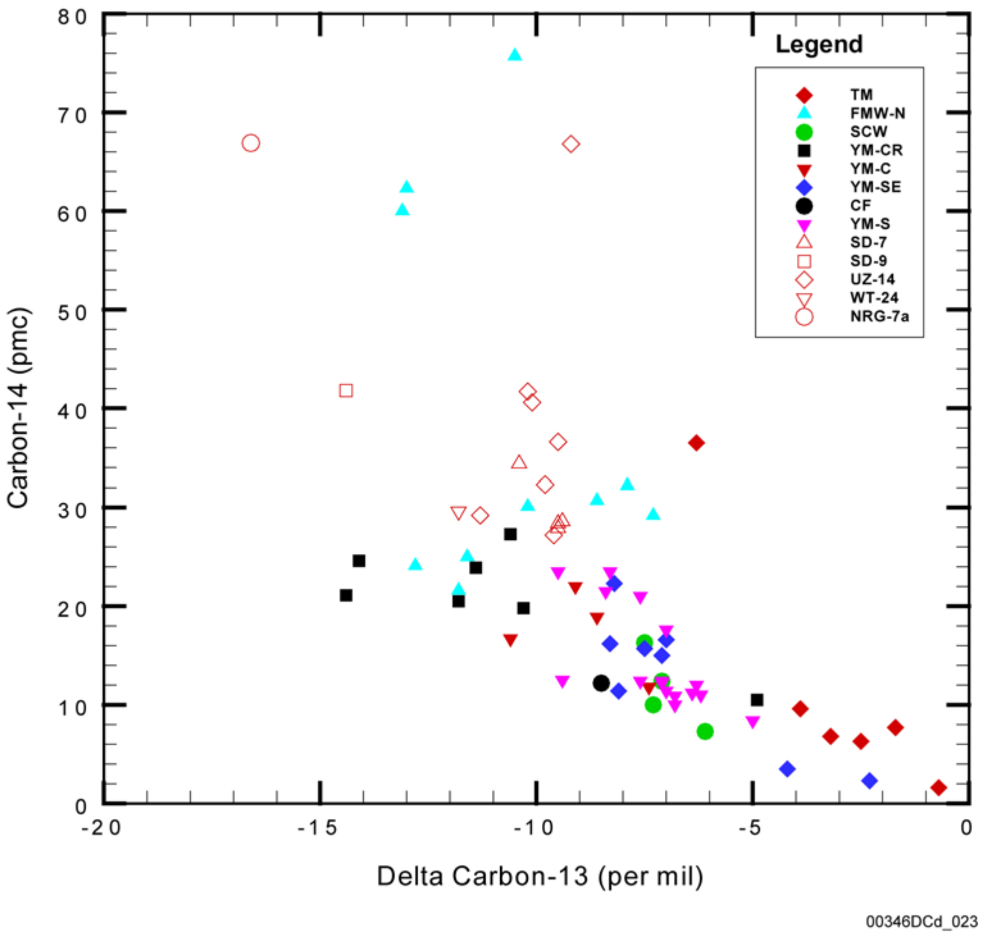
- **Single hole injection-withdrawal tests determine**
  - **range of alluvium fluxes between 1.2 and 9.4 m/yr**
  - **effective porosity of alluvium between 0.05 and 0.3**
- **Site-scale model calculated flux is about 2.3 m/yr for nominal conditions**

# Site Scale Carbon 14 Observations and Interpretation



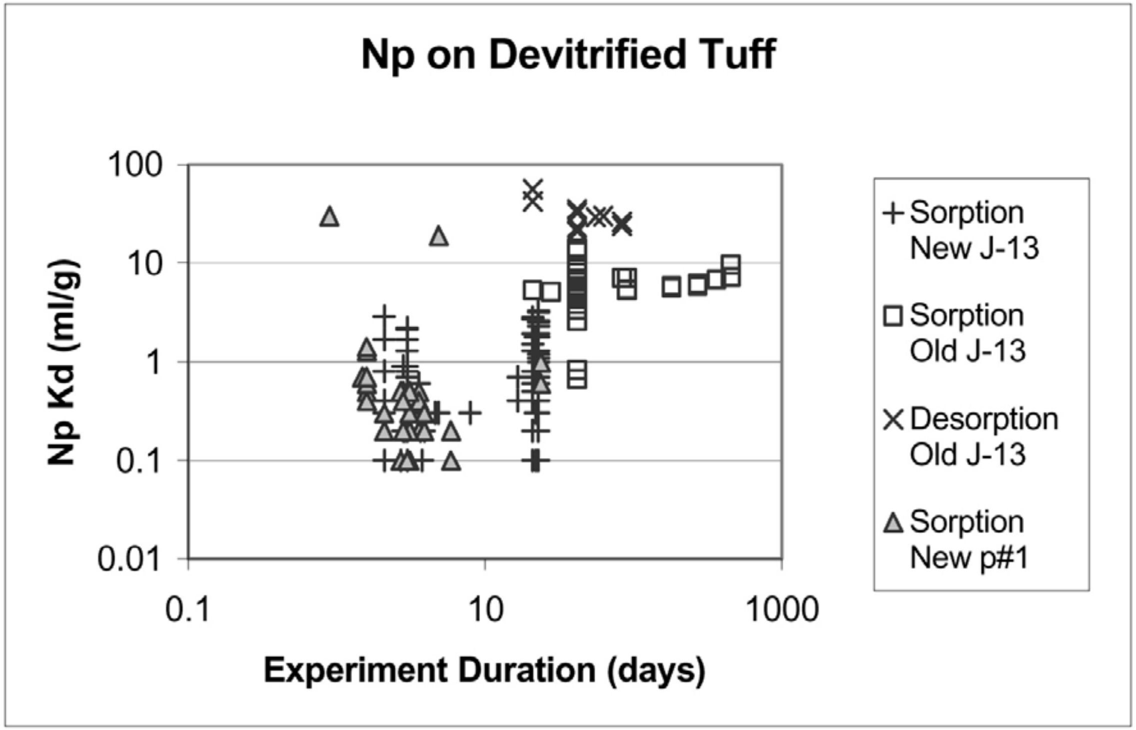

- **Radiocarbon used to investigate groundwater velocities**
- **Carbon-14 (half life of 5700 yrs) has been used to evaluate groundwater ages**
- **Groundwater velocity estimates range from 5 to 40 m/yr (corresponding to advective transport times over 18 km) of several hundred to several thousand years for unretarded species)**

# Carbon-14 versus Delta Carbon-13




- **Filled symbols indicate saturated groundwaters, open symbols indicate perched waters**
- **Increase in Delta Carbon-13 inferred to be due to calcite dissolution along flow path**

# Sorption of Radionuclides on Tuff

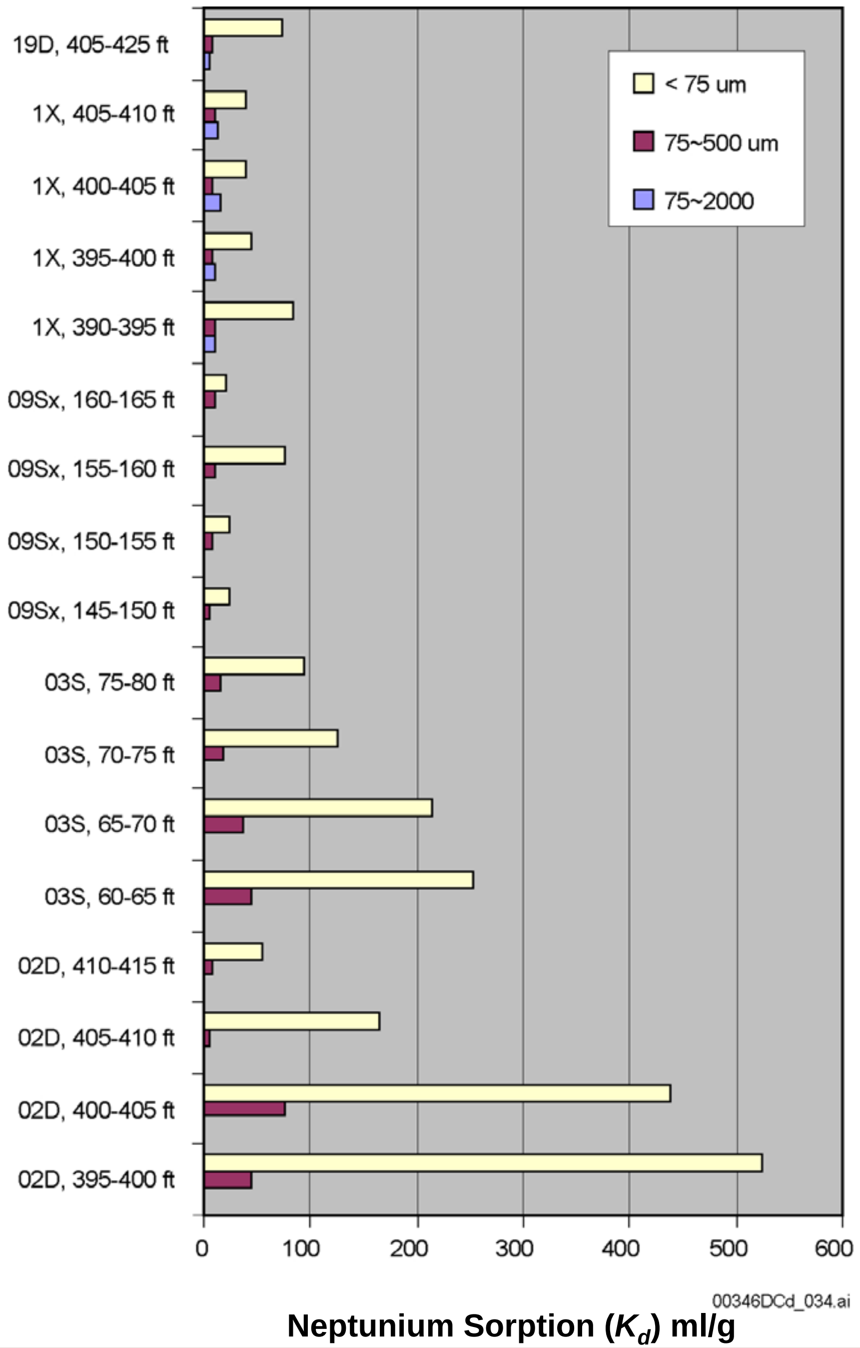



DTN: LA0010JC831341.007, LA0305AM831341.001

NOTE: Experiments oversaturated with $Np_2O_5$ have been omitted.

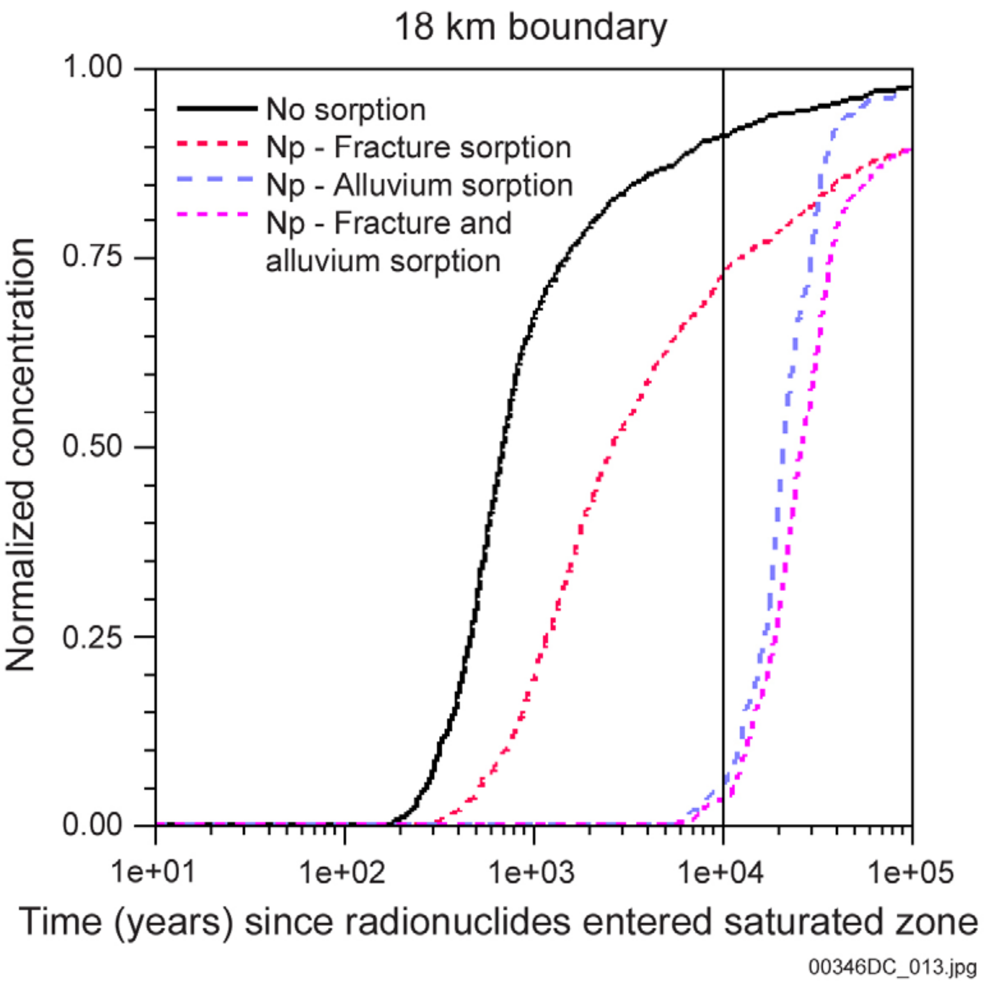
- **Sorption (*$K_d$*) determined in lab tests**
- **Sorption is a function of radionuclide, chemistry and geologic media**
- **Data indicate "old" (pre-1990) and "new" (post-1990) tests using J-13 or p#1 water for both sorption and desorption experiments**

# Sorption of Radionuclides on Alluvium



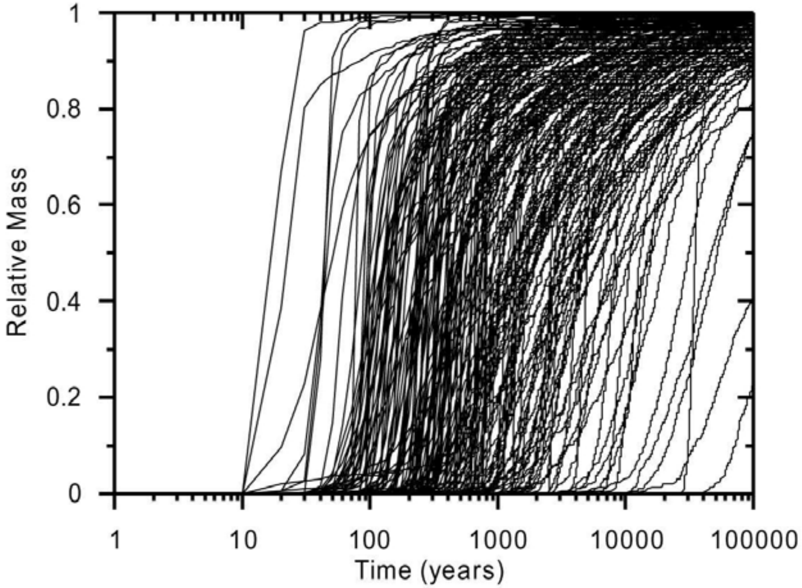

- **Np and U sorption evaluated using alluvium samples from Nye County boreholes**
- **Sorption is a function of grain size as smaller grains have higher percentage of clays**
- **75-2000 micron grain size tests only conducted using NC-EWDP-19D and -1X samples**

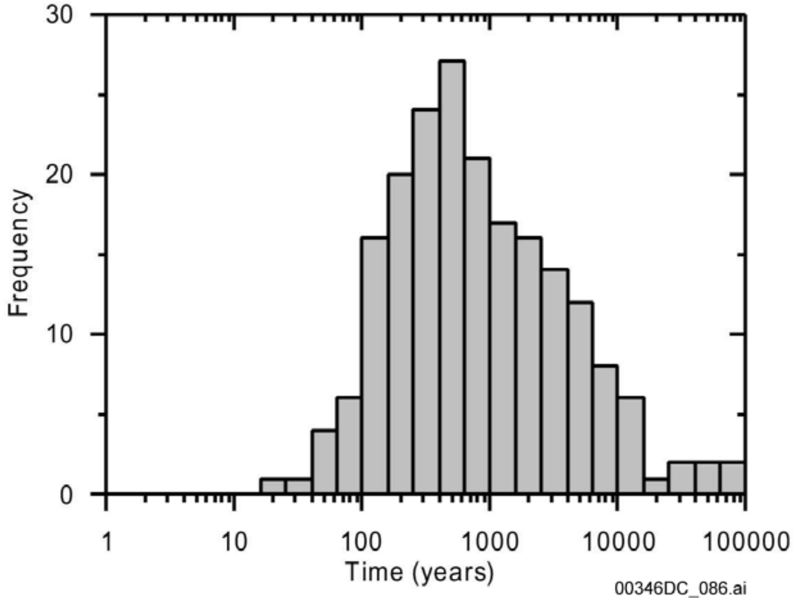
# Calculated Radionuclide Mass Breakthrough




- **Plot indicative of nominal properties**
- **Mass flux for non sorbing radionuclides indicates the bulk of the breakthrough occurs between several hundred and several thousand years**
  - **consistent with C-14 interpretations**
- **Moderately sorbing species (Np-237) only ~ 5% breakthrough at 10,000 years**

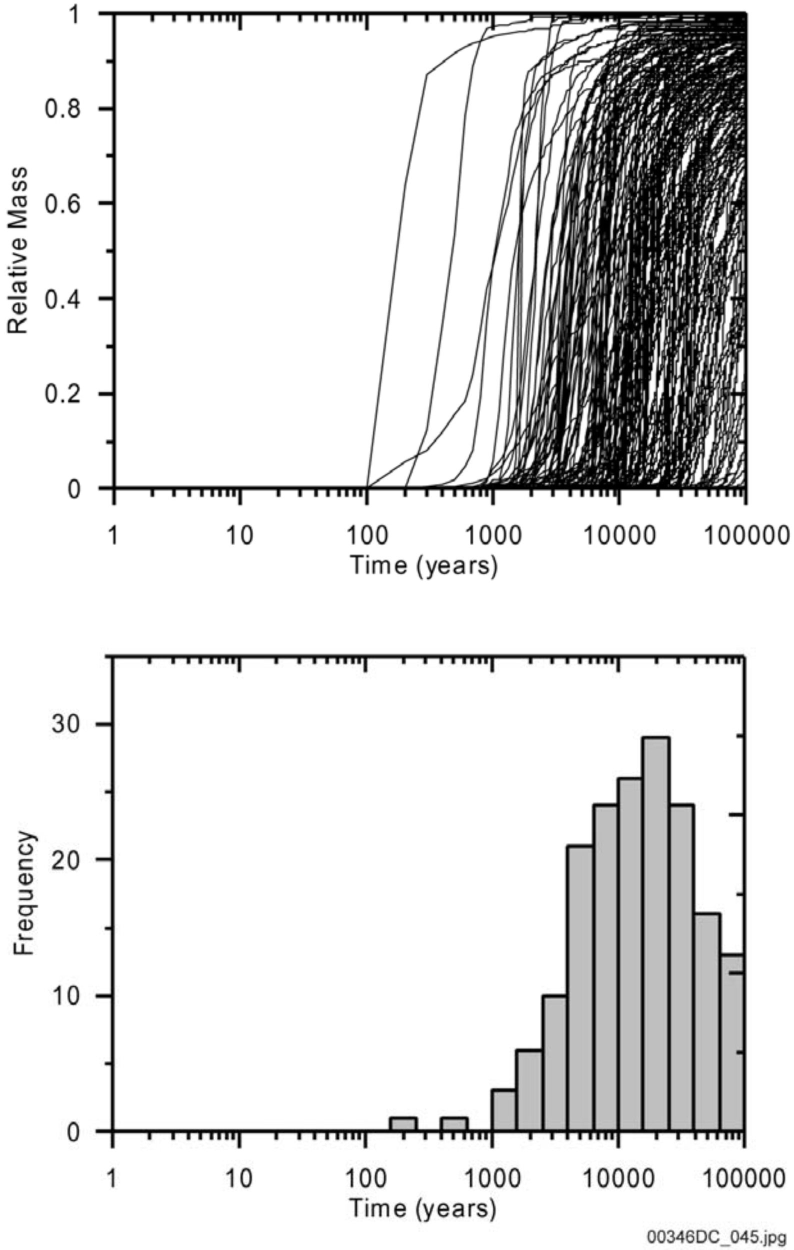
# Calculated Radionuclide Breakthrough – Technetium




- **Technetium is a non-retarded radionuclide**
- **Median Technetium breakthrough occurs at about 500 years with a distribution from less 100 to more than 10,000 years**

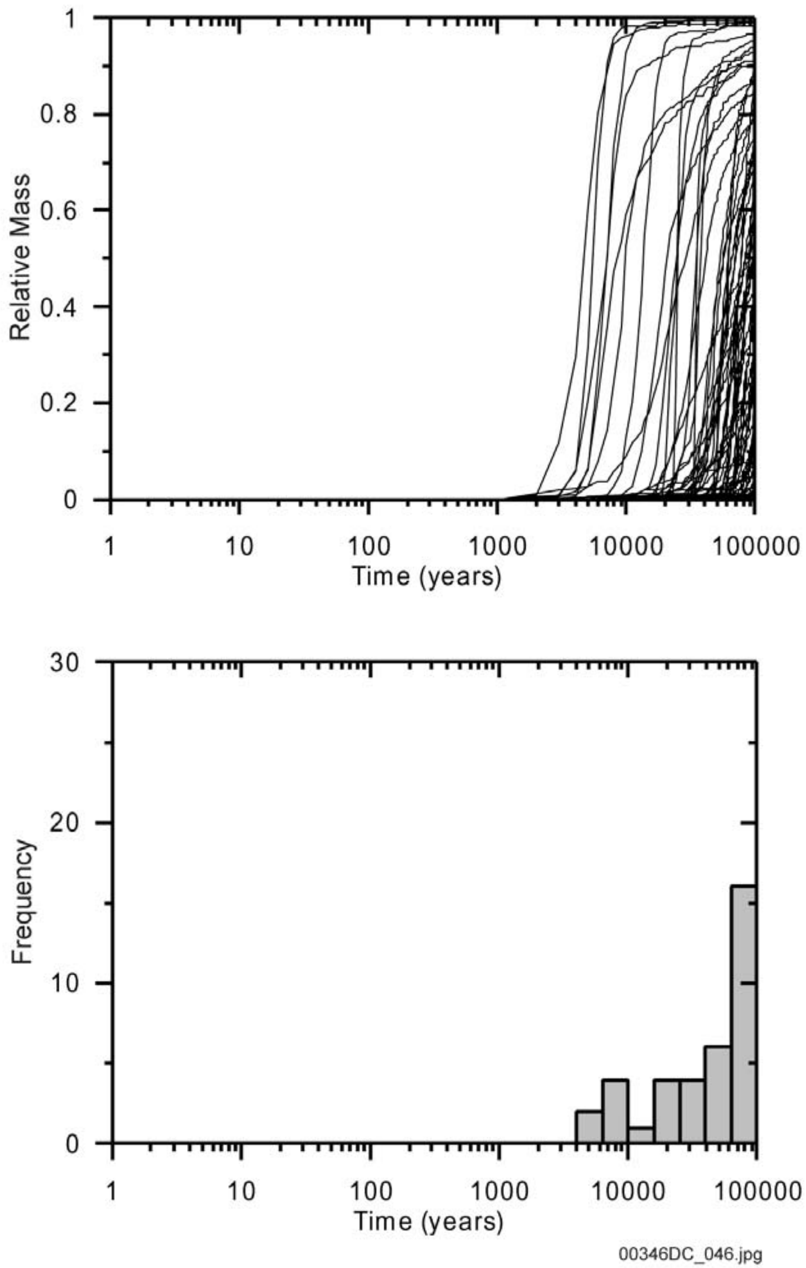
# Calculated Radionuclide Breakthrough – Neptunium




DTN: SN0306T0502103.008 [163947]

- Neptunium is a moderately sorbing radionuclide (Kd between 1 and 10 ml/gm or Rd between about 10 and 100)
- Transport times generally between 1000 and > 100,000 yrs
- Mode of breakthrough distribution at about 20,000 years

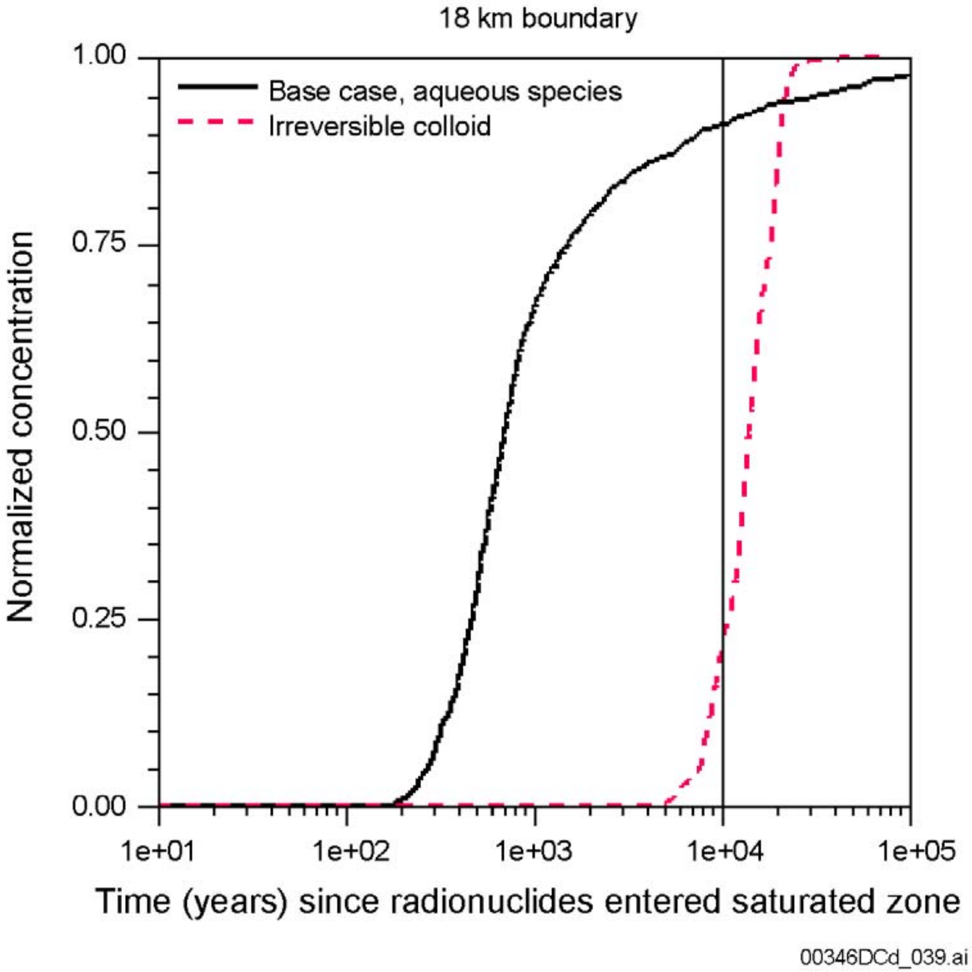
# Calculated Radionuclide Breakthrough – Plutonium (dissolved)




DTN: SN0306T0502103.008 [163947]

- Uncertainty in breakthrough indicates about 5% breakthrough before 10,000 years
- Distribution of breakthroughs between < 10,000 years and > 100,000 years

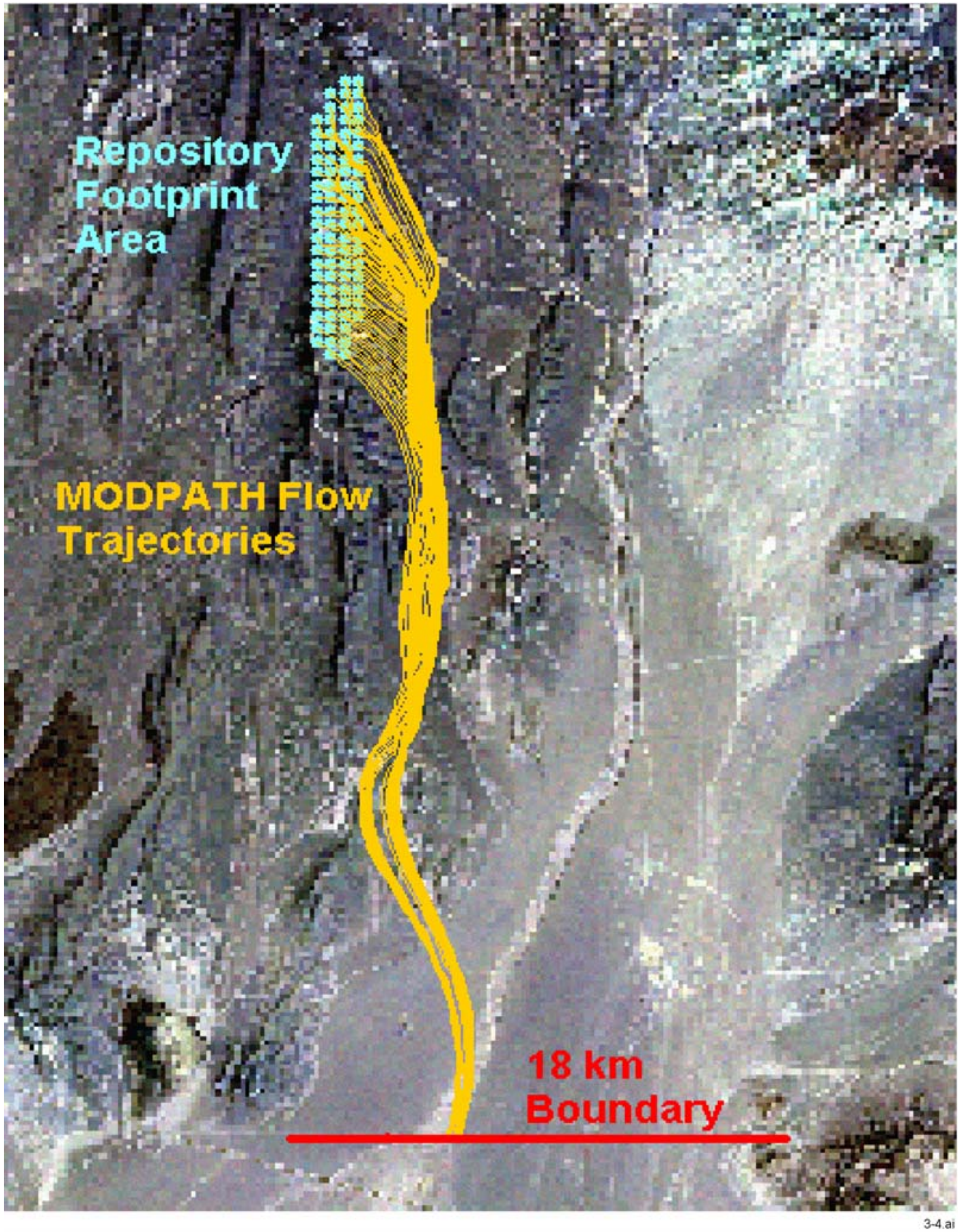
# Calculated Radionuclide Breakthrough – Plutonium (colloidal)




- **Colloid transport is significantly delayed from non sorbing radionuclides due to filtration-type processes**
- **Colloid transport parameters developed from tests using analog microspheres in C-Wells**

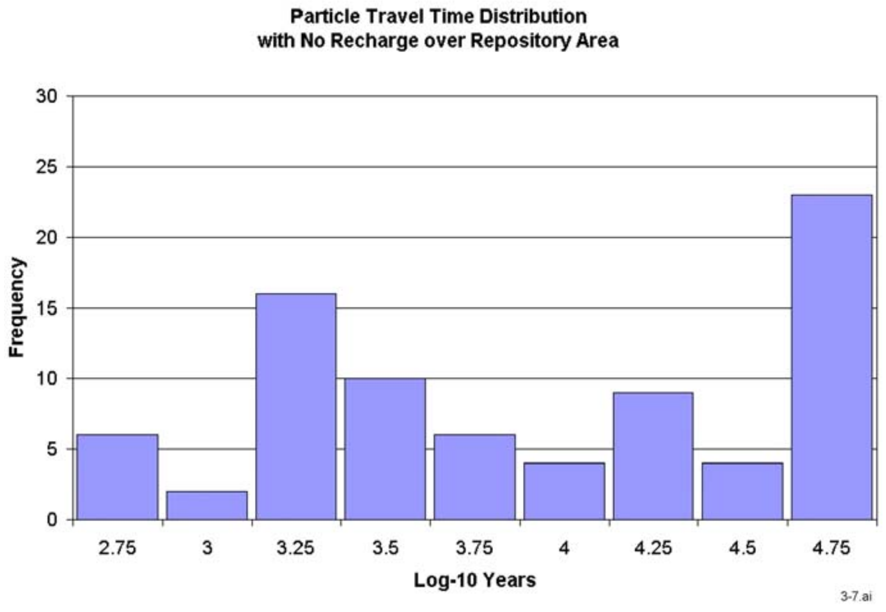
# Comparison to Alternative Representations Developed by NRC/CNWRA Staff

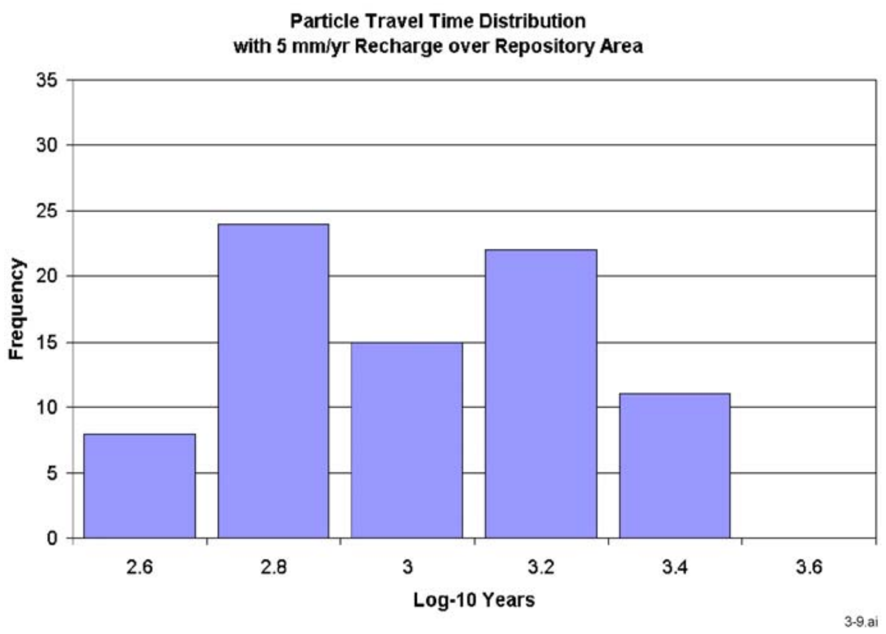
- The Center for Nuclear Waste Regulatory Analysis has developed several models of saturated zone flow and transport
- Winterle 2002 provides CNWRA analyses of alternate conceptual models of geologic structure and hydrologic boundary conditions on saturated zone flow and transport
- The results of these analyses are presented here for information only
- None of the cases presented are favored by NRC to be more representative of actual conditions




# NRC/CNWRA Flow Model Results

- Flow paths are similar to those based on site-scale flow model
- Increased southerly flow the result of enhanced north-south anisotropy




# NRC/CNWRA Transport Model Results

- Particle travel times represent non retarded radionuclide advective-dispersive transport times
- Similar results to our travel time distributions except at low end of advective transport times

# Summary and Conclusions – Groundwater Flow

- Saturated zone flow models developed to evaluate flow directions and rates
- Flow models are constrained by regional water budget and geochemistry and site-specific hydraulic heads and permeabilities
- Flow model projects travel paths generally southeasterly and then southwesterly
- Flow model predicts fluxes in the range of 0.7 to 2.3 m/yr
- These fluxes are reasonably constrained by Carbon 14 ages and a single well tracer test in the alluvium
- The fraction of the flow path in the alluvium is a function of the flow path and ranges between 1 and 10 km

# Summary and Conclusions – Radionuclide Transport

- Effective flow porosities in the tuff and alluvium have been determined from tracer tests
- Effective transport velocities developed from the flow and transport model yield transport times of between several 100 and several 1000 years for unretarded species
- These transport times are consistent with Carbon-14 ages
- Confirmation of matrix diffusion and sorption processes have been confirmed in field tests
- Sorption characteristics of radionuclides have been determined in range of laboratory experiments

# Summary and Conclusions – Results of Barrier Performance

- **Projections of saturated zone performance indicate a range of performance varying between 100's to 1,000's of years for non sorbing radionuclides (Tc, I, C), 1,000's to 10,000's of years for moderately sorbing radionuclides (Np and U) and more than 10,000 years for highly sorbing radionuclides (Pu, Am)**
- **Uncertainty in key flow and transport parameters has been included in projections of saturated zone performance**
- **Additional drilling and testing continues as part of Nye County Early Warning Drilling Program**