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

UZ and NFE Thermally Driven Coupled Process Components

Presented to:
Nuclear Waste Technical Review Board

Presented by:
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YUCCA MOUNTAIN PROJECT

Participants

- **UZ Flow**
  - J. Wang, G.S. Bodvarsson, J. Hinds, J. Liu, M. Wilson, Y.-S. Wu
- **Thermally Driven Coupled Processes Effects on Flow (Mountain-Scale)**
  - C. Haukwa, G.S. Bodvarsson, J. Rutqvist, E.L. Sonnenthal, C.-F. Tsang, M. Wilson
- **Seepage**
  - S. Finsterle, R. Ahlers, G.S. Bodvarsson, G. Li, C.-F. Tsang, M. Wilson, Y.-S. Wu

Participants
(Continued)

- **Thermally Driven Coupled Processes Effects on Seepage (Drift-Scale)**
  - Y. Tsang, S. Blair, G.S. Bodvarsson, T. Buscheck, C.K. Ho, J. Rutqvist, E.L. Sonnenthal, N. Spycher, C.-F. Tsang,
- **Multiple Lines of Evidence**
  - A. Simmons, P. Dobson, J. Stuckless

Objectives of the Presentation

- Present recent advances in UZ and NFE Studies since TSPA-SR
  - Unquantified Uncertainties
  - Examined range of thermal operating modes
- Describe resolution of uncertainties
- Use of multiple lines of evidence

UZ Flow Developments since TSPA-SR

- **Unquantified Uncertainties**
  - Examined lateral flow in the PTn
  - Expanded 3-D flow fields
- **Thermally Driven Coupled Processes (Mountain Scale)**
  - Thermal Hydrologic (TH)
    - Includes lithophysae on thermal properties
    - Examine range of thermal operating modes

UZ Flow Developments since TSPA-SR

(Continued)

- Thermal Hydrologic Chemical (THC)
  - New model development—addresses processes beyond scope of drift-scale THC models
- Thermal Hydrologic Mechanical (THM)
  - New model development—addresses multi-phase flow and calculates stress induced permeability changes

Seepage Developments since TSPA-SR

- **Unquantified Uncertainties**
  - Expanded seepage model to include Tptpll
  - Reduced conservatism in flow focusing factor
  - Used a more realistic 3-D drift degradation seepage model
- **Thermally Driven Coupled Processes (Drift Scale)**
  - TH, THC, THM—Models modified to include lithophysae cavities on thermal properties in the Tptpll
  - TH, THC, THM—examined range of thermal operating modes
  - THM—Developed fully coupled THM Continua Model

Treatment of Uncertainty

- **Addressed uncertainties in:**
  - **Conceptual models**
  - **Parameters**
  - **Input data**
- **Reduced uncertainty through:**
  - **Analysis of new data from previously untested units**
  - **Analysis of new data from improved experiments**
  - **Extended sensitivity analyses**
  - **Evaluation of multiple lines of evidence**

Multiple Lines of Evidence

Gained confidence in approach through:

- **Natural analog studies**
- **Additional laboratory and field experiments**
- **Detailed process modeling**
- **Comparison with alternative approaches**

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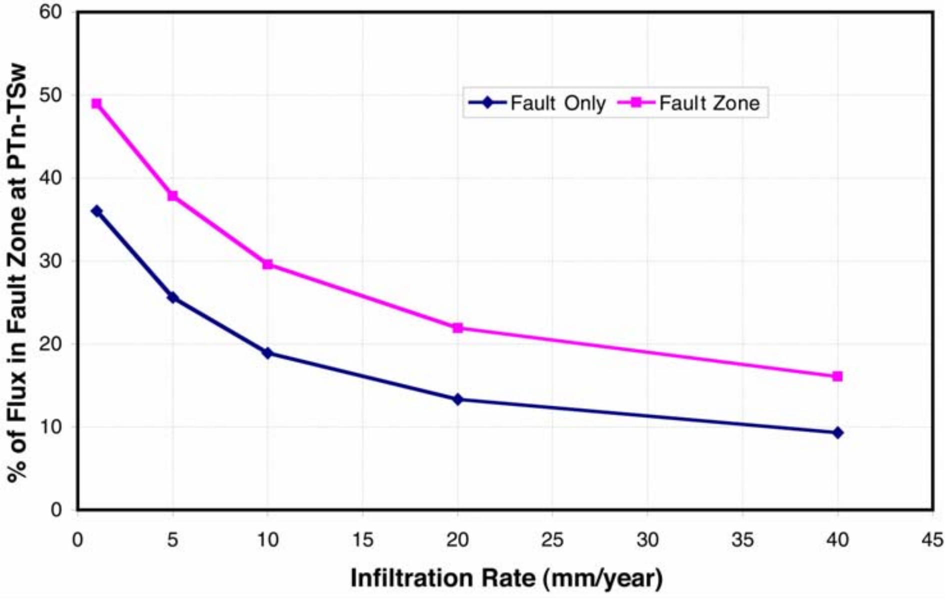
Lateral Flow in the PTn

- Comparison of the impact of net-infiltration rates on percentage of flow through faults and fault zones
- At the present-day mean net-infiltration rate, about 25 percent of the percolation flux is laterally diverted into faults within the PTn
- This lateral flow effect has not been propagated to TSPA (conservative assumption)



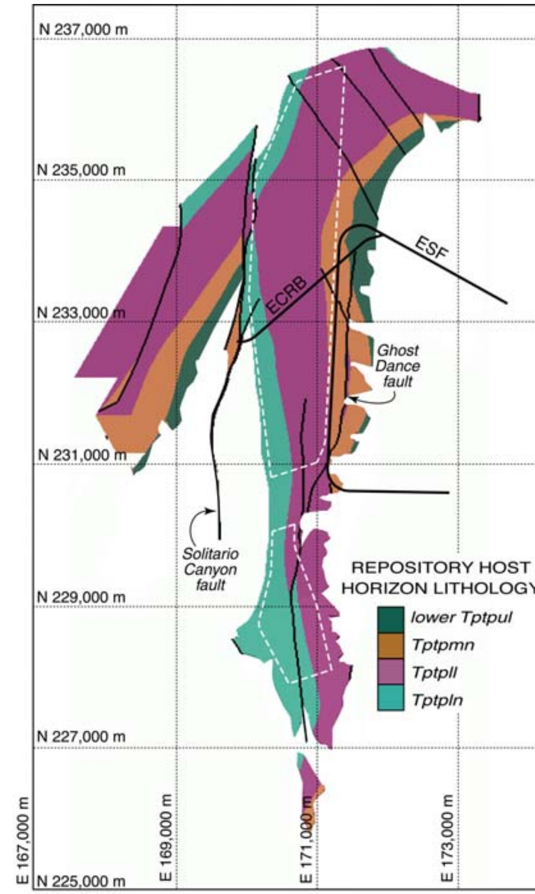
Incorporation Into TSPA

Mountain Scale UZ Flow Processes Investigated		In TSPA	Future Plans for TSPA	Comments
Unquantified Uncertainties	Lateral Flow in the PTn	No	Yes	Conservative to neglect
	New Potential Repository Footprint	No	If needed	Inclusion depends on design
Thermally Driven Coupled Processes	TH	No		Screens out changes to flow fields
	THC	No		Screens out changes to flow fields
	THM	No		Screens out changes to flow fields

Drift-Scale UZ Flow Processes Investigated		In TSPA	Future Plans for TSPA	Comments
Unquantified Uncertainties	Expansion of Seepage – Tptpll	Yes		
	Flow Focusing	Yes		Reduced effect compared to baseline
	Drift Degradation	No	Yes	Reduced effect compared to baseline
Thermally Driven Coupled Processes	TH	Yes		
	THC	No	Yes	
	THM	No	Yes	Could result in increased diversion of seepage

3-D Flow Fields —
Repository Potential Horizon Lithology

- **Available siting area at the repository horizon showing the potential horizon lithology**
- **Note potential southern expansion area**
- **Standoff to Solitario Canyon Fault not considered in calculating available area**
- **Effects of expanding the repository footprint for lower temperature designs has limited effect on the 3-D UZ flow fields**



UZ Flow —
Multiple Lines of Evidence

- **Rainier Mesa—Underground excavations used to study precipitation vs. infiltration—draw parallels for groundwater travel times and fast flow regimes**
- **Percolation Flux Studies at Yucca Mountain using geochemical and temperature data agree well with current estimates of percolation flux**

UZ Flow Developments since TSPA-SR

- **Unquantified Uncertainties**
  - **Examined lateral flow in the PTn**
  - **Expanded 3-D flow fields**
- ***Thermally Driven Coupled Processes (Mountain Scale)***
  - ***Thermal Hydrologic (TH)***
    - ***Includes lithophysae on thermal properties***
    - ***Examine range of thermal operating modes***
  - ***Thermal Hydrologic Chemical (THC)***
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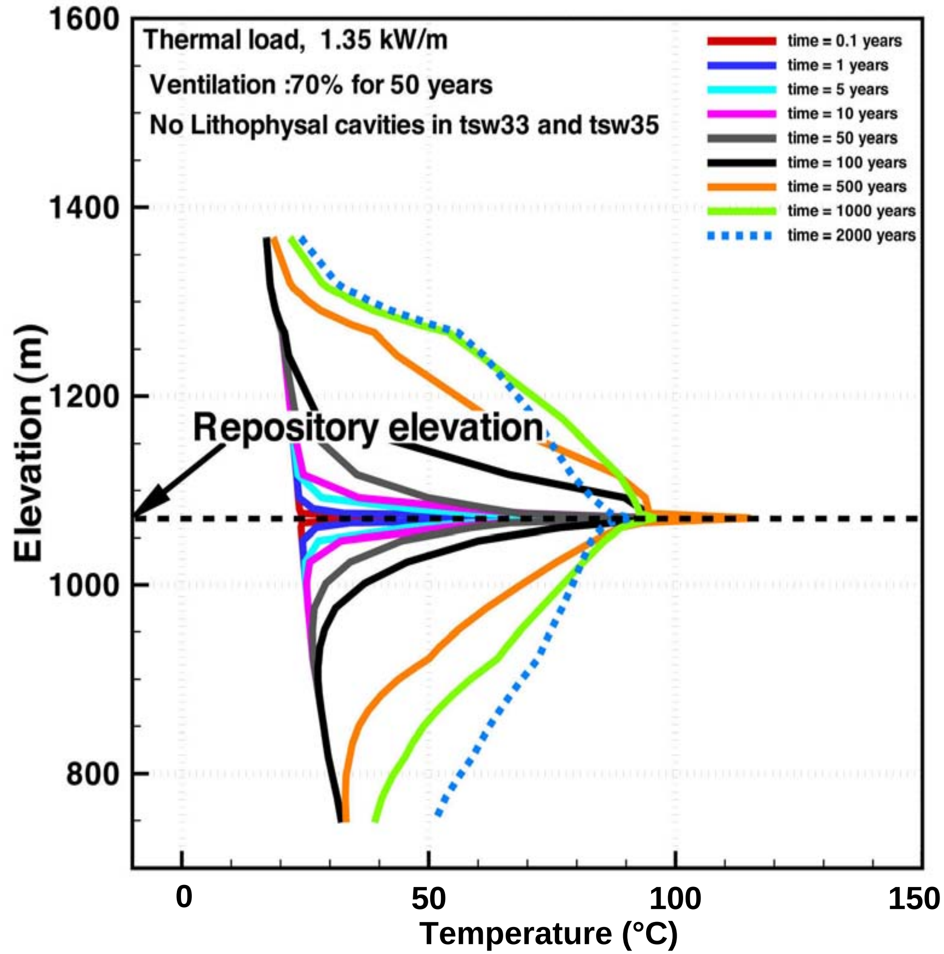
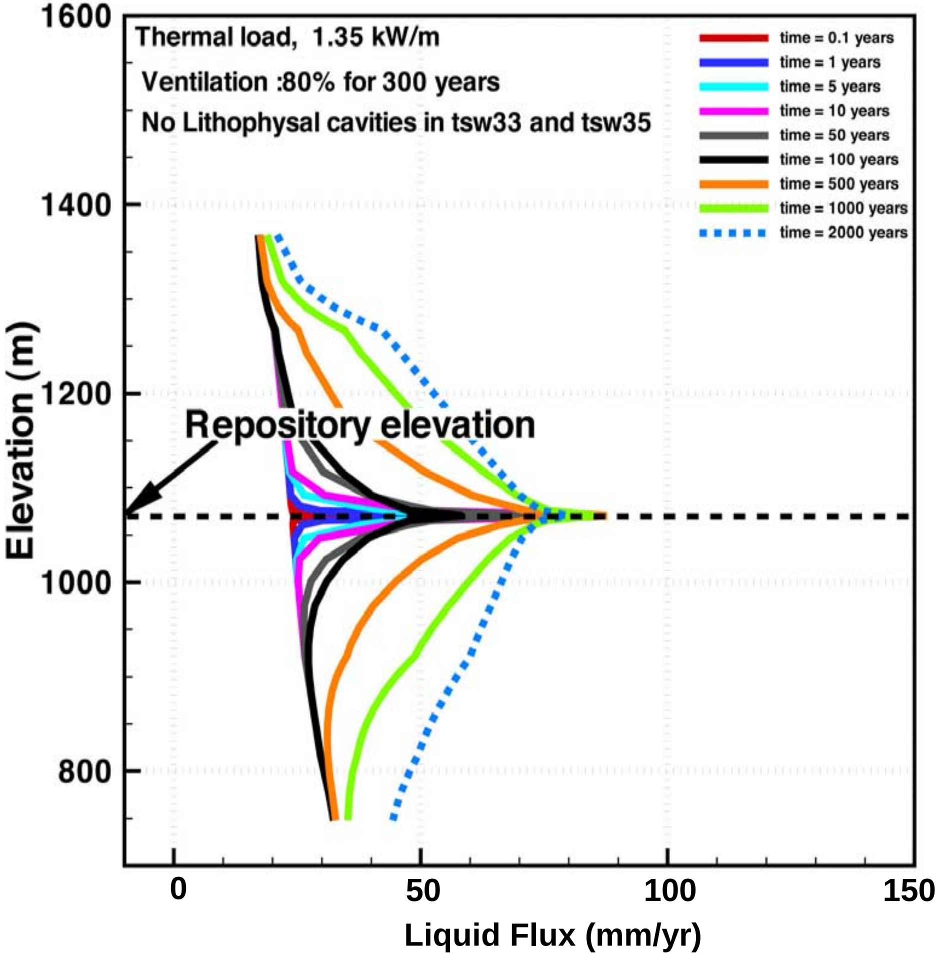
TH-Mountain Scale — Temperature Profiles for Higher Temperature Case

- Temperature profiles near the center of the repository are studied with and without lithophysal cavities
- In both cases, the TH model predicts completely dry drifts with temperatures rising above boiling after 500 years
- Used to screen out mountain-scale TH from TSPA

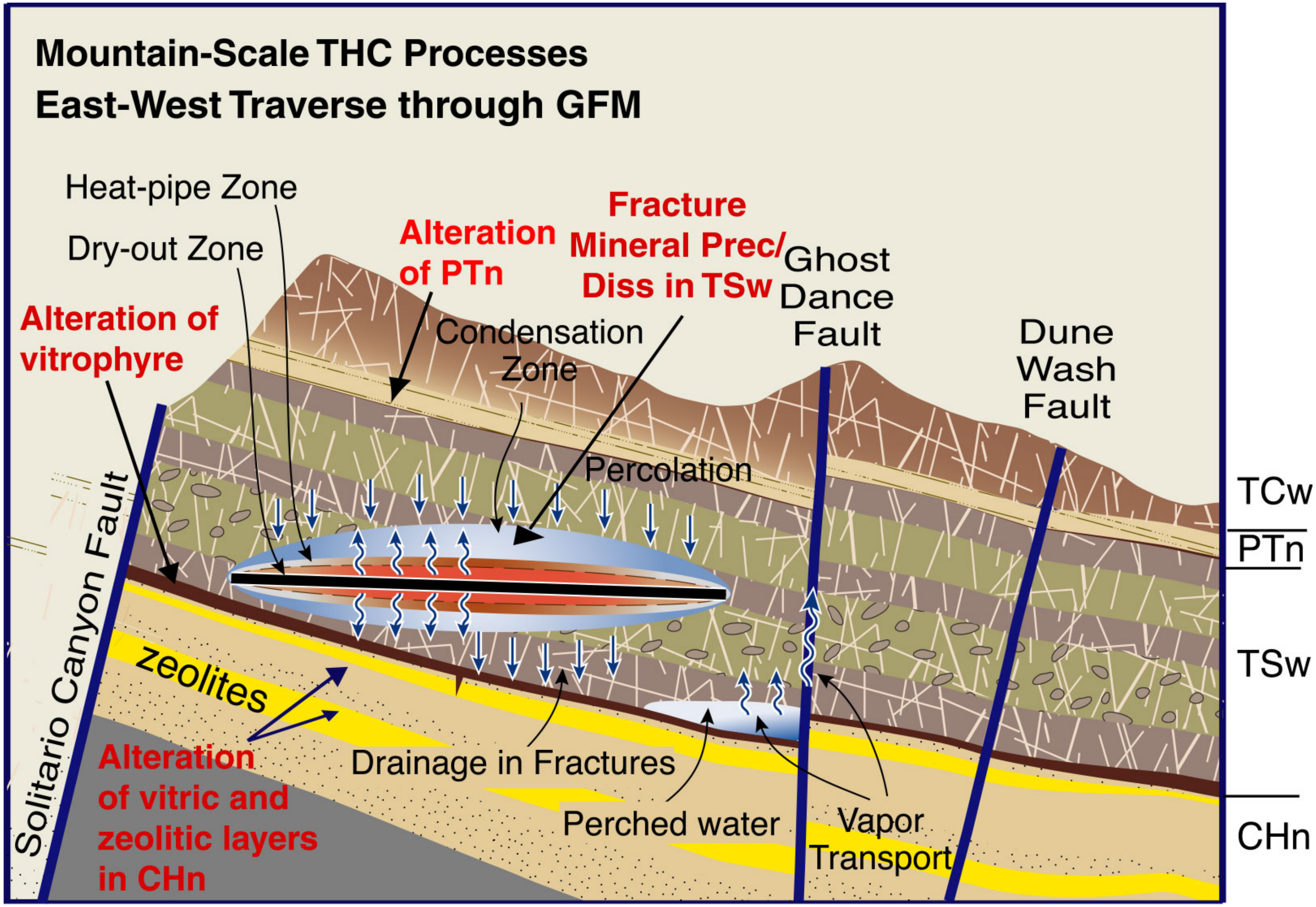


TH-Mountain Scale — Temperature and Saturation for Lower-Temperature Case

- **Temperatures never reaches 90°C, with the highest temperature being reached after 500 years**
- **Significant vaporization and condensation does not occur at the repository elevation; liquid flux crosses the host horizon relatively unimpeded**
- **Used to screen out mountain-scale TH from TSPA**

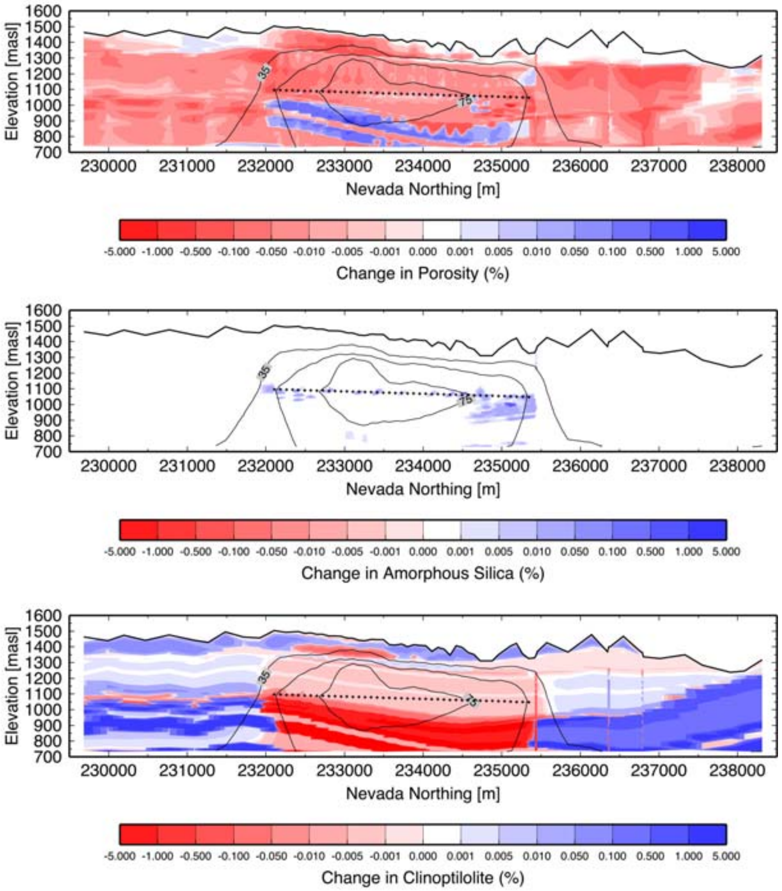


THC-Mountain-Scale Coupled Processes



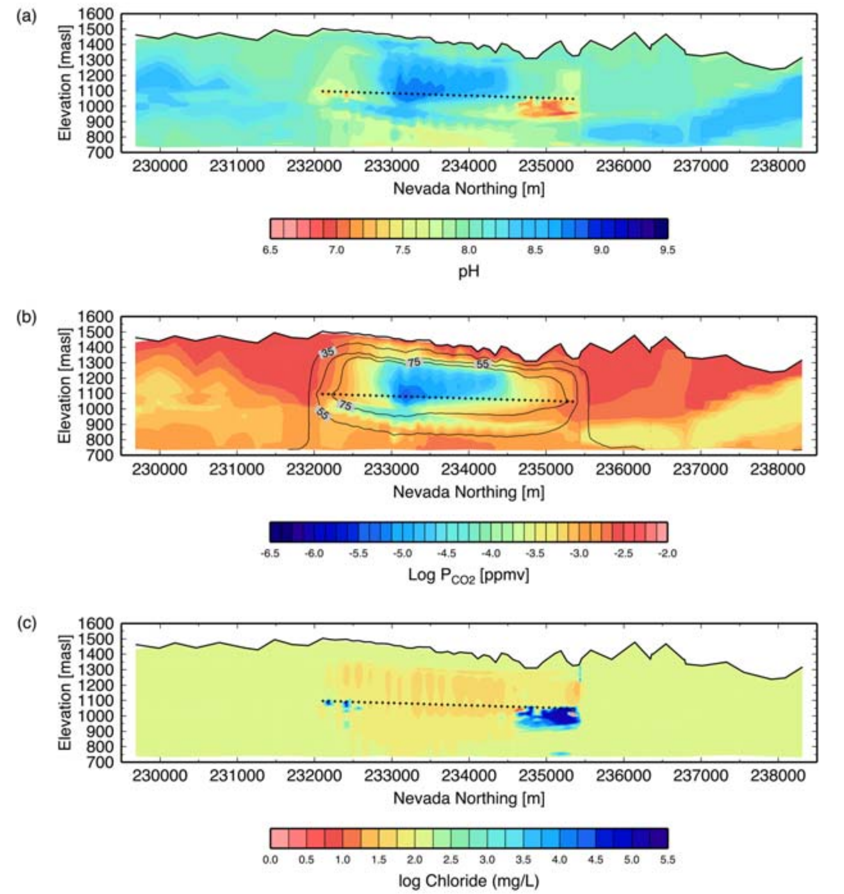
THC-Mountain Scale — Changes in Porosity and Mineralogy

- **The region above and directly below the repository shows reduction in fracture porosity of less than 1 percent, with greater changes in zeolitic layers**
- **Precipitation of amorphous silica also occurs below the northern edge of the repository owing to gas convection**
- **Matrix clinoptilolite (zeolite) dissolves to form feldspars, also progressing into zeolitized regions of the TCw**
- **These preliminary model studies suggest that mountain scale THC effects have little impact on 3-D UZ Flow Fields**



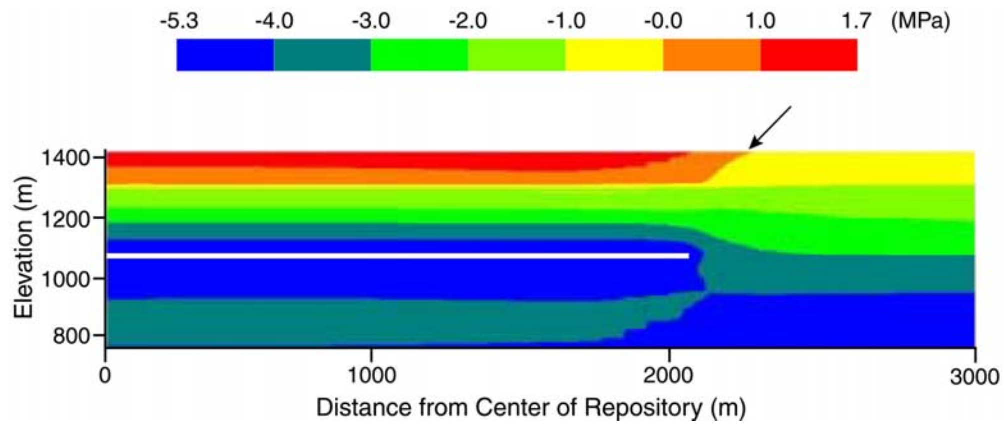
THC-Mountain Scale— Water and Gas Chemistry

- The area in the center of the potential repository has somewhat higher pH waters forming above and around the drifts
- CO_2 loss in the potential repository center is a result of degassing and reactions with aluminosilicates
- Chloride concentrations reflect reductions by dilution from condensation and increases owing to boiling and evaporation through gas convection
- Effects on seepage chemistry included in TSPA



THM–Mountain Scale Coupled Processes

- Horizontal stress distribution at 1,000 years is due to THM effects around the repository
- Changes in vertical and horizontal permeability are due to THM effects
- Permeability factor ranges from 0.3 to 2.75, indicating minor impact (except near ground surface)



Units	Elevation (m)	K_v/K_i	K_H/K_i
TCw	1447–1326	1.0 to 38	1.0 to 38
PTn	1326–1291	1.24 to 2.55	1.28 to 2.75
TSw31	1291–1289	1.80	2.27
TSw32	1289–1250	0.58	0.98
TSw33	1259–1167	0.40	0.72
TSw34(tptpmn)	1167–1134	0.28	0.66
TSw35(tptpll)	1134–1030	0.47 to 0.77	0.75 to 0.89
TSw36–37	1030–981	0.83 to 0.85	0.92 to 0.93
TSw38–39	981–960	0.53 to 0.72	0.80 to 0.88
CHn-pp4	960–869	0.9 to 1.0	1.0 to 1.1
Pp3_bf3	869–730	1.1 to 1.2	1.1 to 1.2

Source: derived from Bodvarsson 2001 [DIRS 154669], Attachment 9, pp. 1 to 78.

NOTE: K_v = vertical permeability; K_H = horizontal permeability; K_i = initial permeability.

Mountain-Scale Thermally Driven Coupled Processes Multiple Lines of Evidence

- **TH and THC—Validation through small-scale experiments (e.g., Single-Heater Test and Drift-Scale Test)**
- **THC—Yucca Mountain alteration mineralogy, isotope geochemistry, and fluid inclusion data used to elucidate THC history of tuffs**
- **THM—TM/THM experiments conducted in the G-tunnel in Rainier Mesa used to evaluate permeability changes associated with heating**

Seepage Developments since TSPA-SR

- ***Unquantified Uncertainties***
  - ***Expanded seepage model to include Tptpll***
  - ***Reduced conservatism in flow focusing factor***
  - ***Used a more realistic 3-D drift degradation seepage model***

- **Thermally Driven Coupled Processes (Drift Scale)**
  - **TH, THC, THM—Models modified to include lithophysae cavities in the Tptpll**
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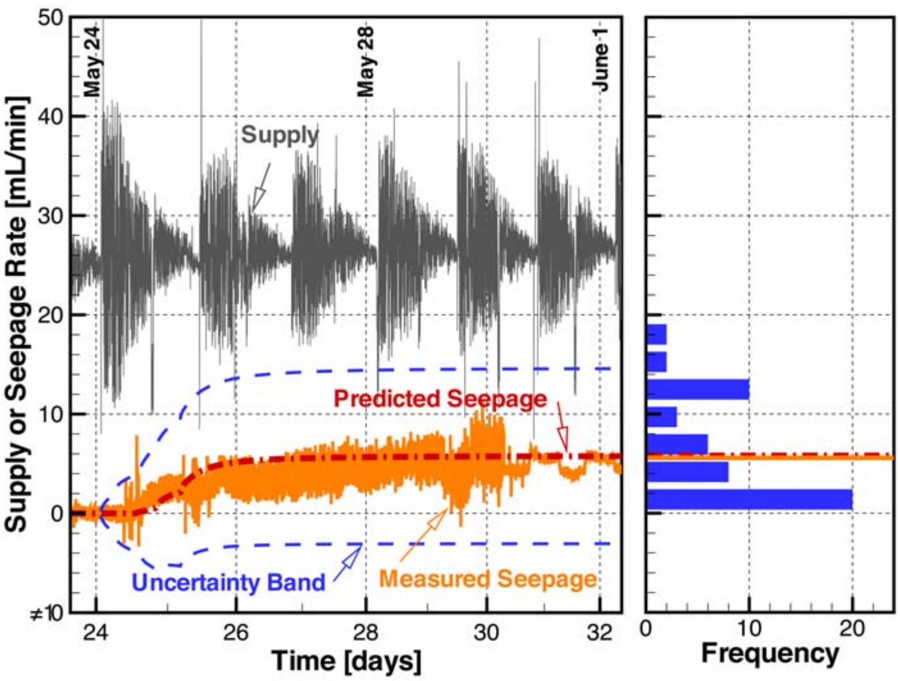
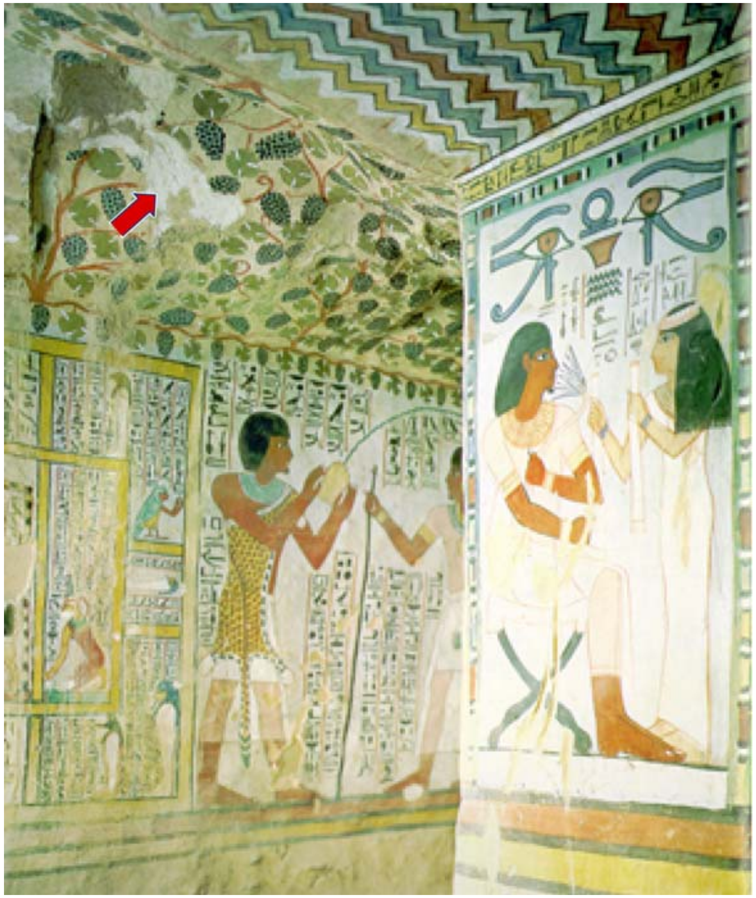
Drift-Scale Seepage — Determination of Seepage Rate Uncertainty

- **Prediction of seepage-rate experiment compared against near-steady seepage-rate data**
- **The seepage rates obtained with the best-estimate parameter set very accurately predict the late-time data**
- **Histogram of simulations using stochastic permeability fields indicates uncertainty**
- **Seepage for Tptpll included in TSPA**



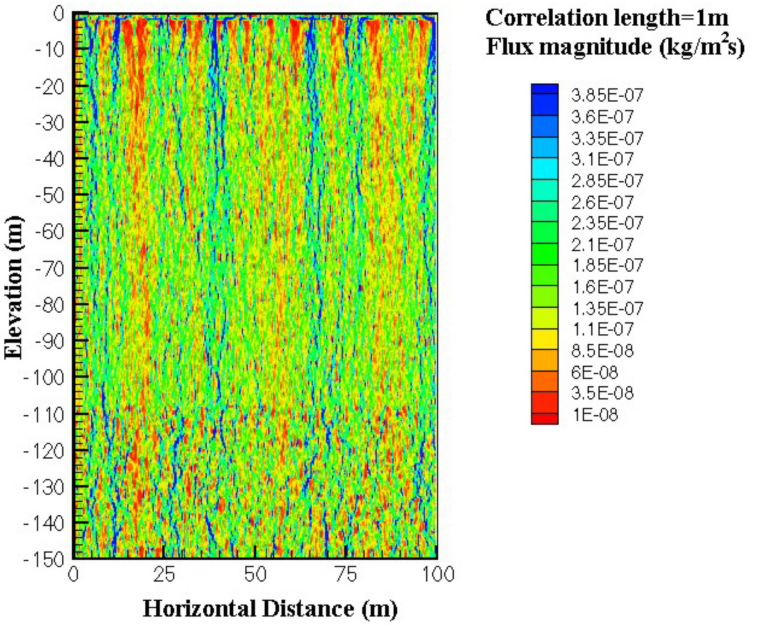
Drift Seepage — Multiple Lines of Evidence

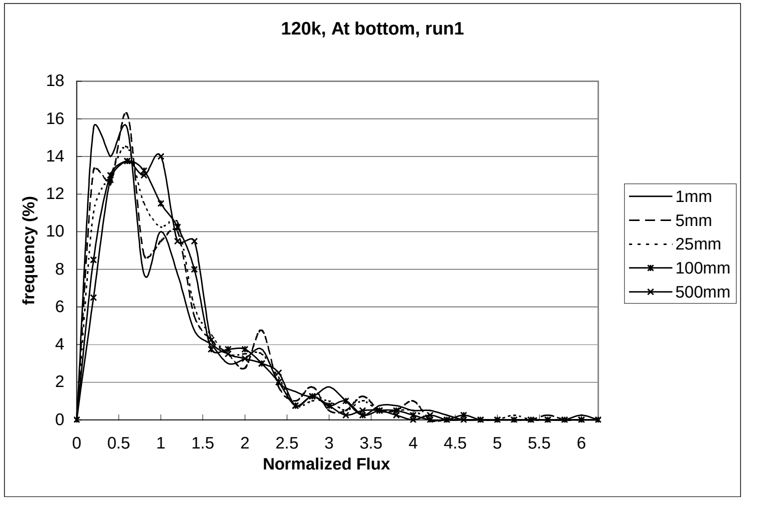
- **Egyptian tombs excavated in limestone about 3,500 to 3,000 years ago present a useful analog for seepage into drifts**
- **In the tomb of Sennefer, small areas of spallation of plaster from walls and ceilings are seen, but evidence of dripping is lacking**



Flow Focusing

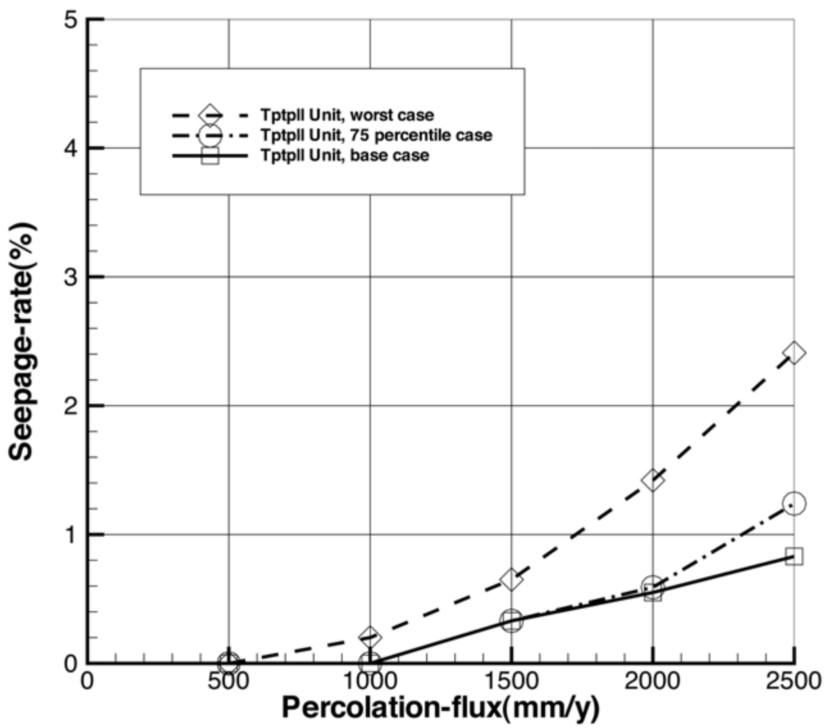
- Distribution of simulated liquid percolation flux assumes uniform percolation at the upper boundary with a stochastic permeability field
- Numerous near-vertical, high-flux, discrete flow paths develop
- The resulting distribution of vertical fluxes shows that the flow-focusing factor is always less than 6
- New flow focusing factors are involved in TSPA





Drift Degradation Effect on Seepage

- Simulated seepage into degraded drifts takes into account increased fracture permeability and increased area. Results are shown here for a range of degradation scenarios
- Drift degradation has a small effect on seepage threshold. Seepage rates are only moderately increased due to the increased area



Seepage — Multiple Lines of Evidence

- **Seepage and seepage barriers—both natural and man-made underground openings**
  - **Archeological cave sites**
  - **Egyptian tombs**
  - **Lithophysal cavities**
  - **Excavated tunnels at Rainier Mesa**
  - **Ongoing seepage tests at Yucca Mountain**
- **Flow focusing and fast flow paths**
  - **Chlorine-36 bomb-pulse signals**

Seepage Developments since TSPA-SR

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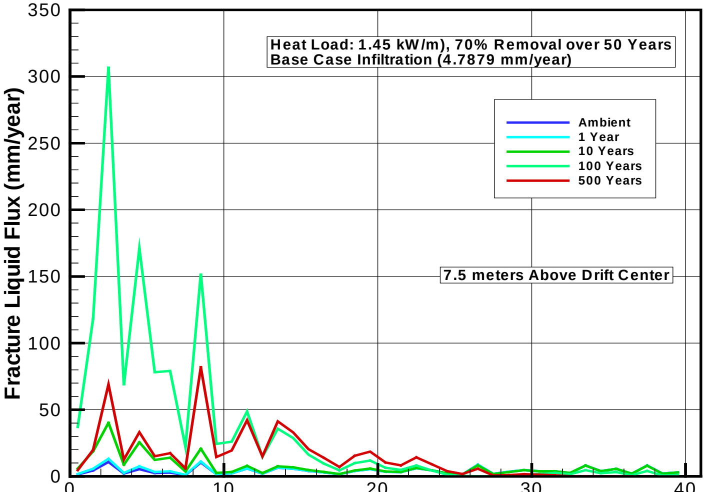
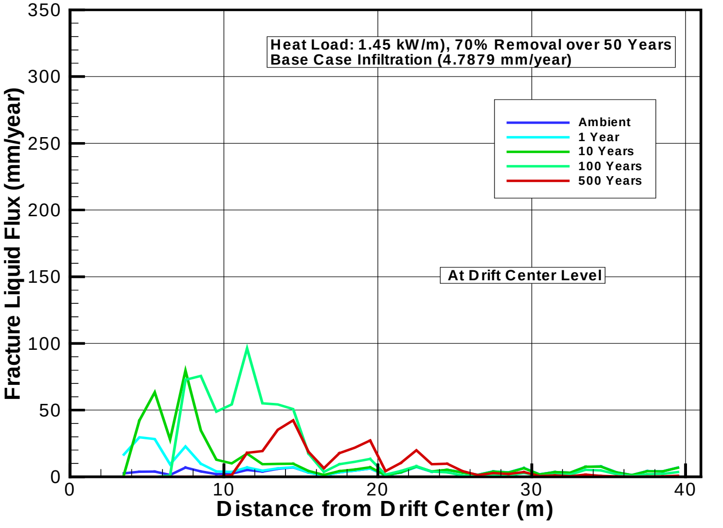
TH-Drift Scale — Higher Temperature

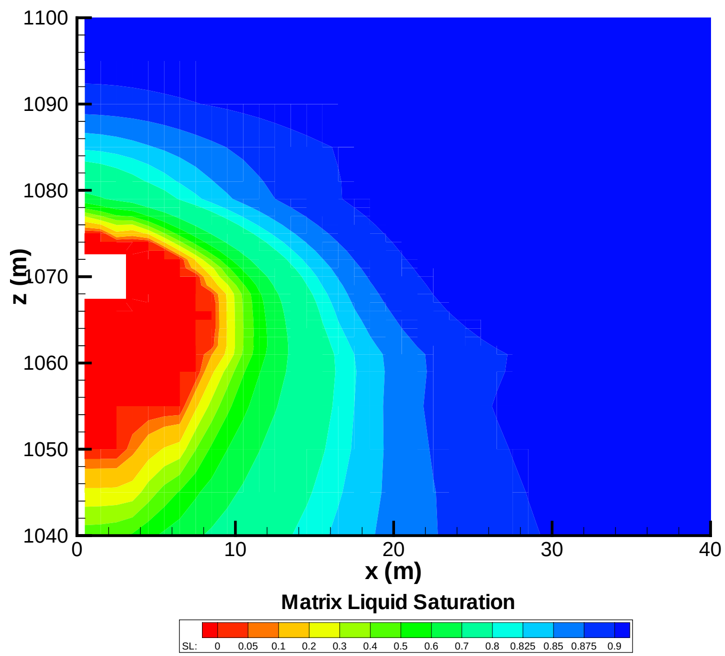
- **Fracture liquid fluxes at different times 5 m above the drift—the fluxes exceed the ambient infiltration rate because of increased fracture saturation in the condensation zone and capillary suction toward the dryout zone.**
- **Fracture liquid fluxes at the drift horizon—none of the enhanced fluxes can cross the drift horizon within the drift.**
- **These results have been incorporated into TSPA**





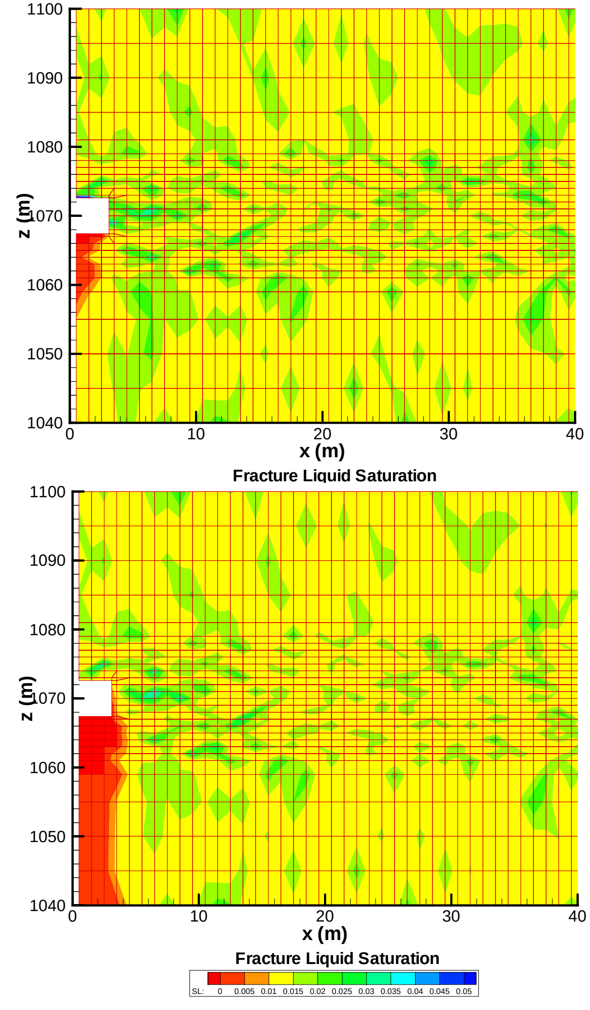
TH-Drift Scale — Higher Temperature

- The liquid saturation distribution in the matrix at 1,000 years after emplacement shows the extent of drying, with a large decrease of the liquid saturation from ambient (about 0.9) to less than 0.01



TH-Drift Scale — Fracture Saturation — Lower Temperature

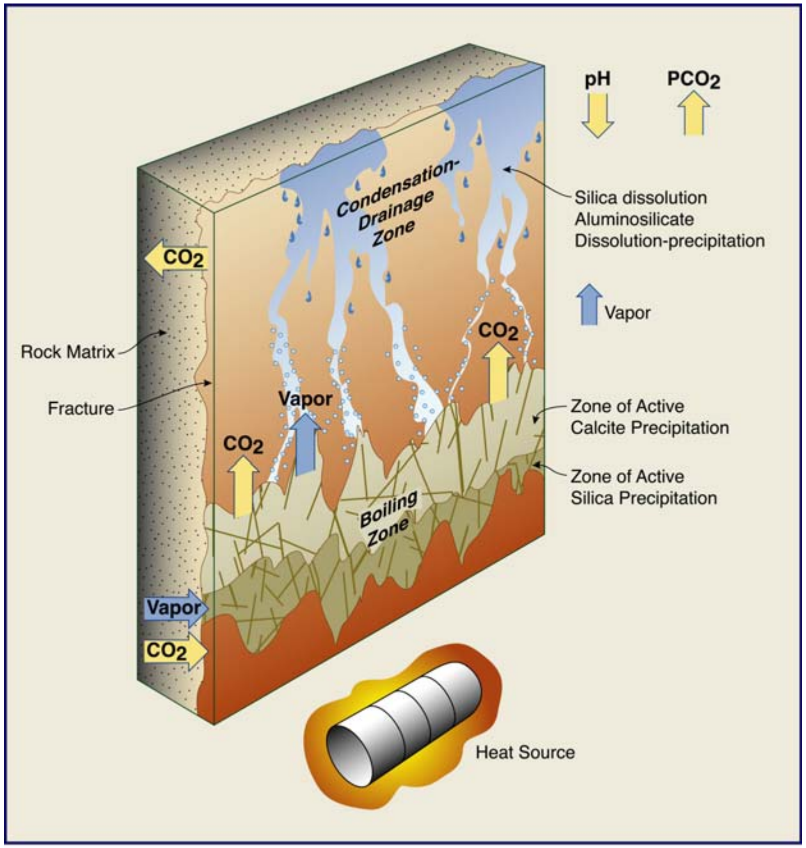
- **Fracture liquid saturations from the lower-temperature operating mode at 50 (top) and 500 years (bottom) after emplacement**
- **Top figure shows a slight increase in saturation immediately above the square drift caused by ponding of downward flux at the drift top (capillary barrier)**
- **The ambient seepage model is directly used in TSPA (slightly conservative)**



TH-Drift Scale —
Reduction of Uncertainty

- **Simulations for a range of thermal operating modes were conducted**
- **Detailed models that include heterogeneity confirmed seepage reduction during thermal period**
- **Analysis of penetration of episodic pulses through superheated rock resulted in very low probability that seepage will occur**
- **Seepage is used for lower temperature cases and the ambient seepage model is directly used for these cases in TSPA**

THC-Coupled Process at Drift Scale

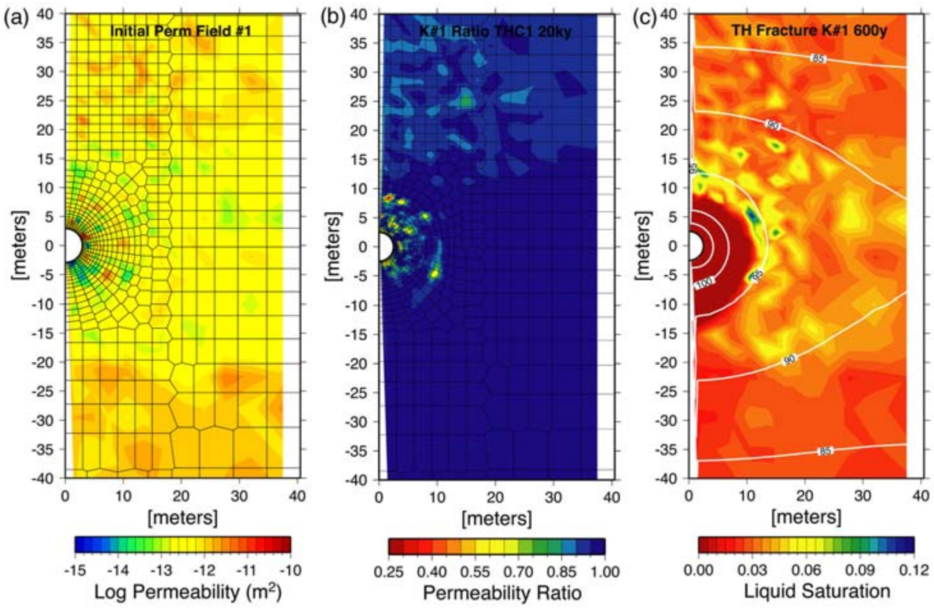


THC Processes

- THC coupled processes may impact seepage through changes in fracture porosity and permeability, capillarity, and fracture-matrix interaction. Also, changes in water chemistry may result from water-rock interaction, evaporation or boiling and condensation, gas-phase interactions, transport processes, and climate changes

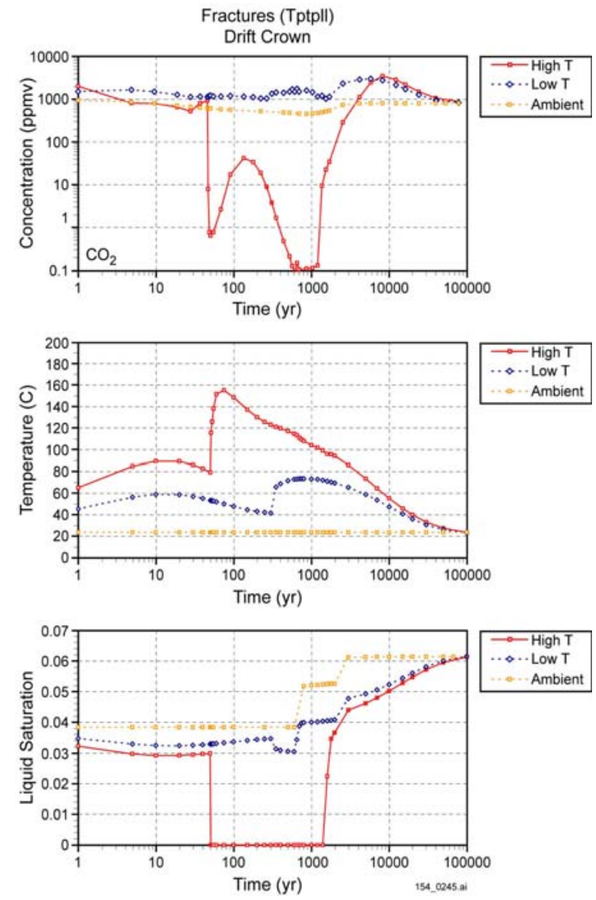
THC-Drift Scale — Permeability Reduction

- Realization of an initial permeability field compared to the percent change in permeability resulting from mineral precipitation after 20,000 years
- Effect of mineral precipitation on permeability is minimal
- Reduction of permeability is greatest in lowest permeability regions
- These results show that THC effects on seepage are minimal



THC-Drift Scale — Chemistry for Higher and Lower-Temperature Cases

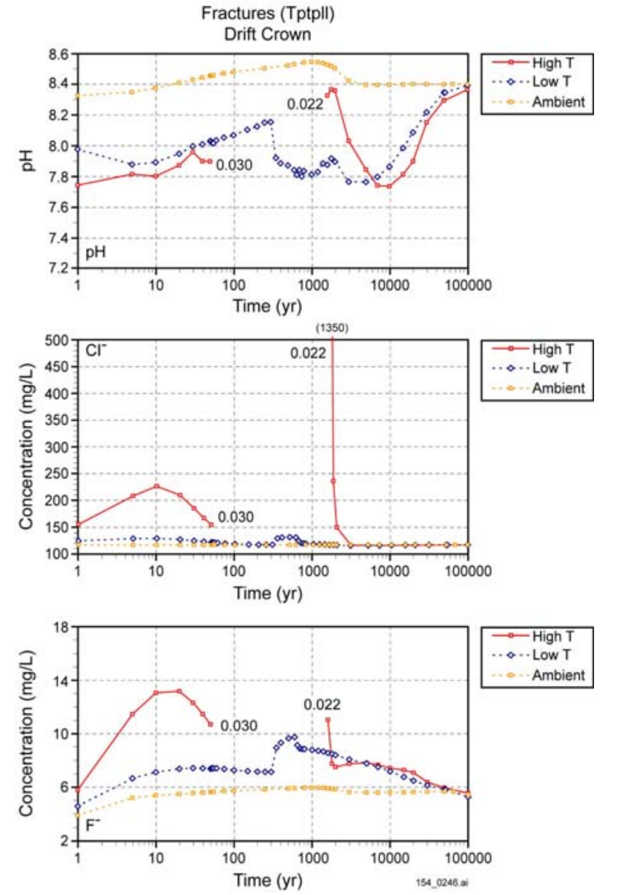
- **Carbon dioxide in fractures at drift crown are shown for the higher-temperature, lower-temperature, and ambient (no heat load) cases**
- **In the higher-temperature case, the drift wall is dry from approximately 50 to 1,600 years**
- **The most pronounced effect of increased temperature on water chemistry is the volatilization of carbon dioxide**



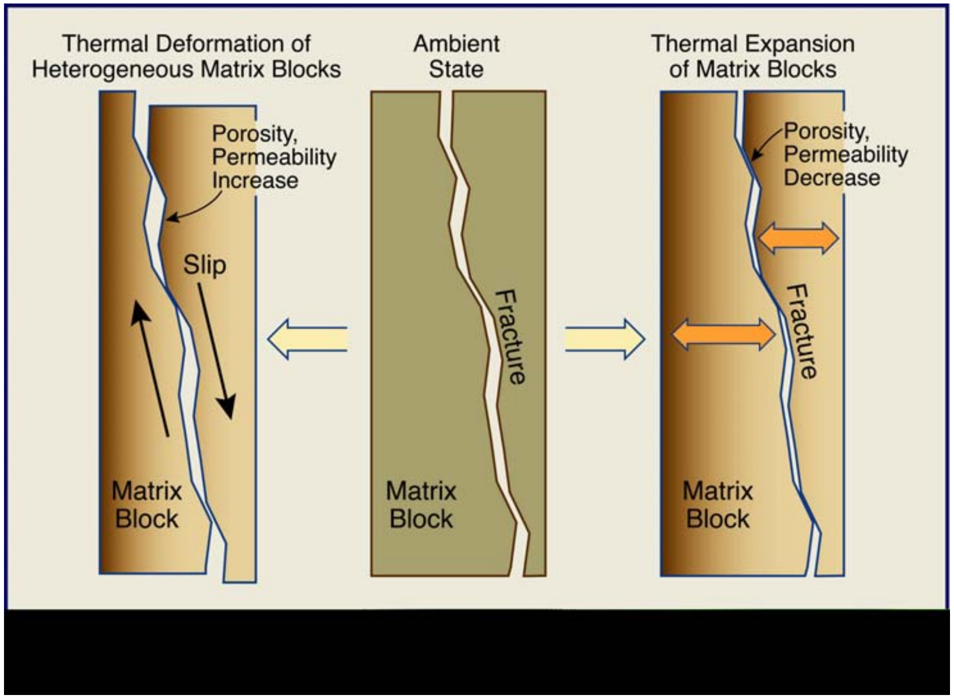
THC-Drift Scale — Chemistry for Higher and Lower-Temperature Cases

(Continued)

- **The bulk of the water present in the rock is contained in the matrix**
- **When heated, carbon dioxide exsolved from matrix water is transported into fractures**
- **Carbon dioxide partial pressure rises above ambient values in fractures**
- **The pH decrease in fracture water is due to condensation**



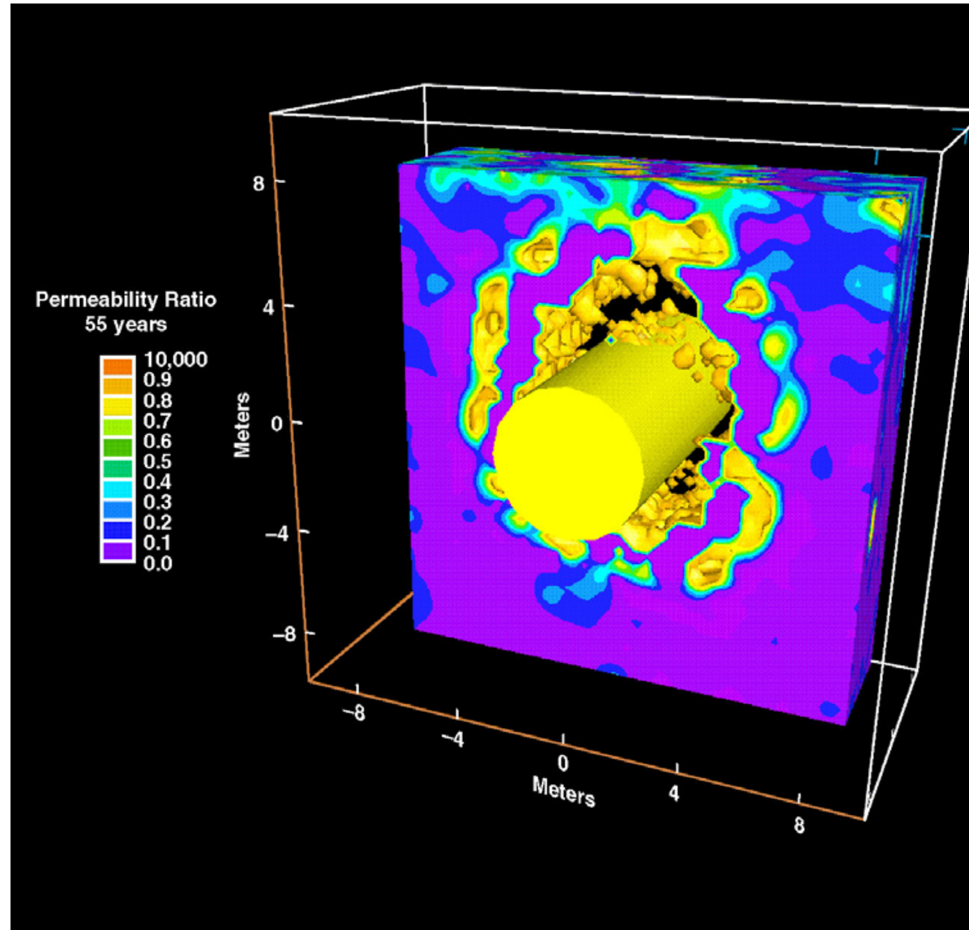
THM-Coupled Processes at Drift Scale



- **THM-coupled processes affect fracture apertures by either opening or closing of fractures, resulting in near-field permeability changes that affect the magnitude and spatial distribution of the percolation flux in the vicinity of the drift, thus influencing seepage threshold and seepage potential**

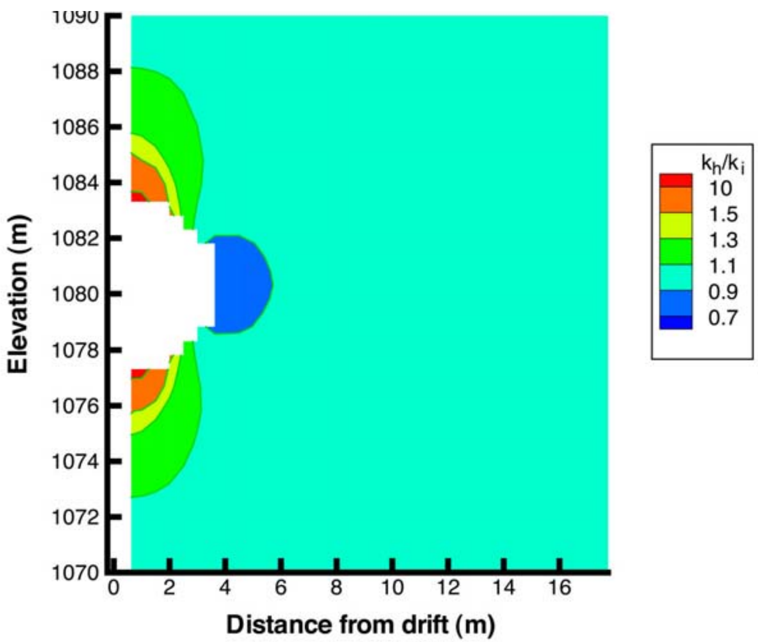
THM-Drift Scale — Distinct Element Model-Higher Temperature

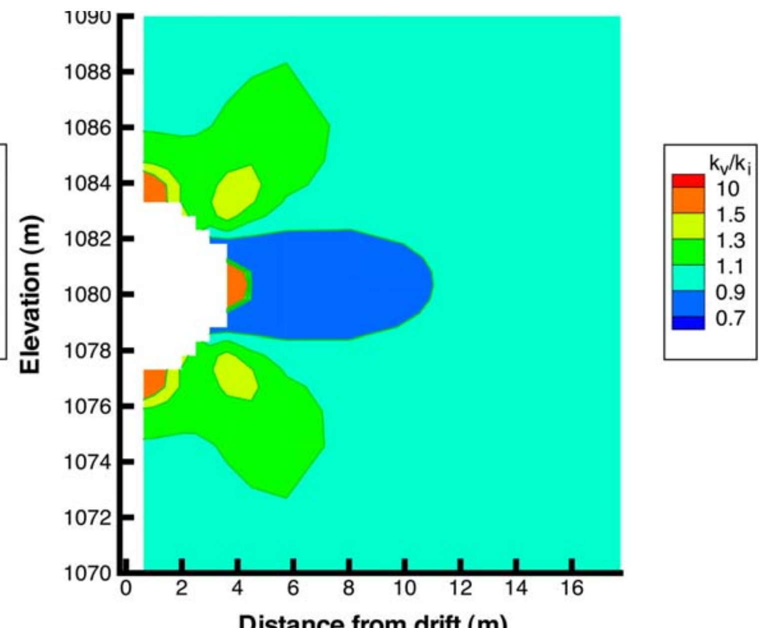
- The distribution of calculated permeability ratios are shown at 55 years
- Note a substantial increase in fracture permeability in the first 2 m of rock forming the emplacement drift wall
- Fracture permeability may also increase in the region above the drift, extending to one drift diameter above the drift crown



THM-Drift Scale — Horizontal and Vertical Permeabilities

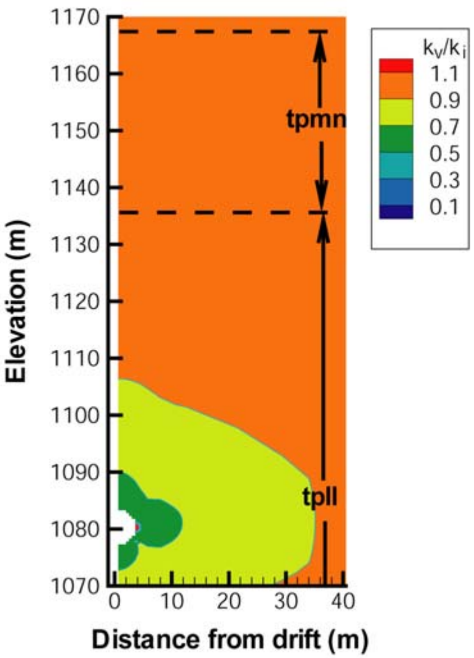
- Changes in vertical and horizontal permeability around the drift are caused by excavation
- Rock permeability increases by a factor of up to 10 above the crown of the drift
- Near the springline of the drift, vertical permeability is increased but horizontal permeability is decreased, resulting in much smaller changes in mean permeability



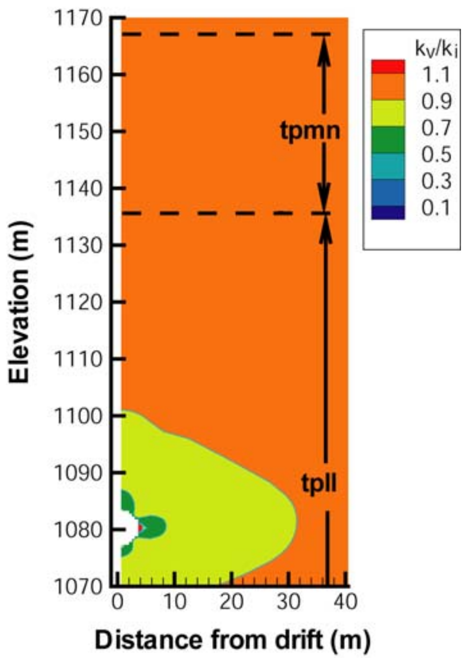


THM-Drift Scale — Vertical Permeabilities for Higher and Lower-Temperature Cases

- At 10 years, both thermal cases show an overall decrease in permeability around the drift due to thermal stress induced by decay heat
- This decrease overcomes the initial excavation- induced permeability increases, except possibly in areas very close to the crown of the drift



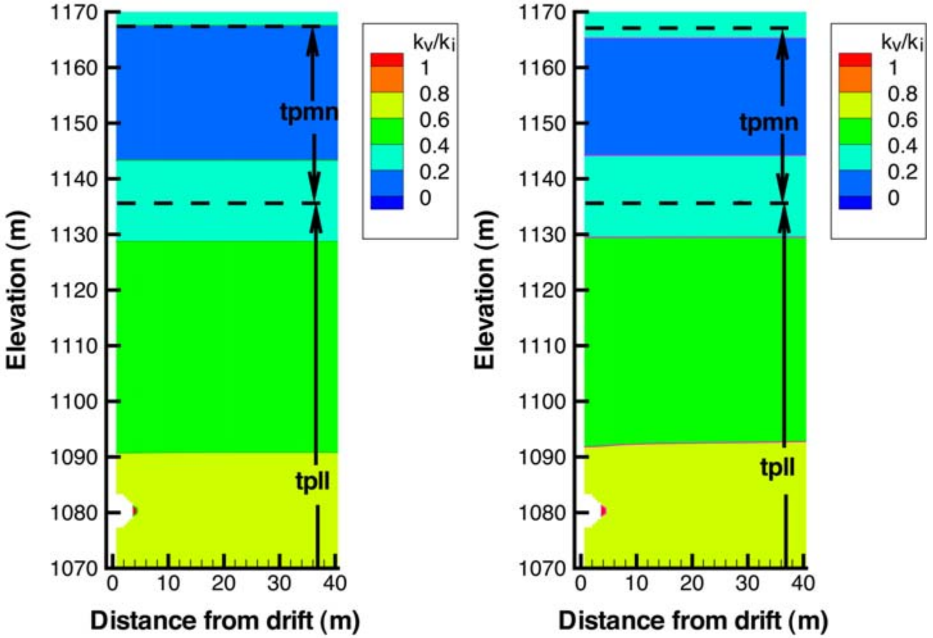
High-Temperature Case



Low-Temperature Case

THM-Drift Scale — Vertical Permeabilities for Higher and Lower-Temperature Cases

- At 1,000 years, for both cases, little or no change occurs in permeability in the lower lithophysal layer (Tptpll)
- Permeability decreases upward toward the middle nonlithophysal layer (Tptpmn), before permeability begins to increase again above this layer
- Effects not included in TSPA
  - Expected to be conservative



High-Temperature Case Low-Temperature Case

THM-Drift Scale — Reduction of Uncertainty

- Development of fully coupled THM model to improve process understanding
- Gained confidence through calibration against Niche and DST data
- Multiple Lines of Evidence include:
  - Nevada Test Site THM experiments
  - Underground testing at Stripa
  - Geothermal analogs

Drift-Scale Thermally Driven Coupled Processes — Multiple Lines of Evidence

- TH—Drainage of water outside an above-boiling region of rock is corroborated by DST observations
- THC—Modeling verified through simulations of tuff dissolution and fracture precipitation experiments
- THC—Active geothermal and fossil hydrothermal systems illustrate impact of temperature, mineralogy, fluid chemistry, and fluid flux on permeability
- THM—Heated block test (at Rainier Mesa) determined effects of excavation, stress, and temperature changes on the permeability of a single joint
- THM—Stripa time-scale heater test showed fracture closure resulting from thermal expansion

Summary and Conclusions

- **Development of more detailed process models supports previous analysis conducted for TSPA-SR**
  - **Gained confidence in conceptualization and overall approach**
  - **Evaluated unquantified uncertainties in both flow and seepage**
  - **Used new information to refine quantified uncertainty**
  - **Broadened the conceptual basis through examination of multiple lines of evidence**
- **Extended thermally driven coupled process simulation over a range of operating modes**
- **Developed new models to examine mountain-scale effects**