# The Underground Test Area Project of the Nevada Test Site: Building Confidence in Groundwater Flow and Transport Models at Pahute Mesa Through Focused Characterization Studies - 10337

Gayle Pawloski*, Jeffrey Wurtz**, and Sigmund Drellack***

*Lawrence Livermore National Laboratory, Livermore, California 94551

**Navarro Nevada Environmental Services, Las Vegas, Nevada 89193

***National Security Technologies, Las Vegas, Nevada 89193

## ABSTRACT

Pahute Mesa at the Nevada Test Site contains about 8.0E+07 curies of radioactivity caused by underground nuclear testing. The Underground Test Area Subproject has entered Phase II of data acquisition, analysis, and modeling to determine the risk to receptors from radioactivity in the groundwater, establish a groundwater monitoring network, and provide regulatory closure. Evaluation of radionuclide contamination at Pahute Mesa is particularly difficult due to the complex stratigraphy and structure caused by multiple calderas in the Southwestern Nevada Volcanic Field and overprinting of Basin and Range faulting. Included in overall Phase II goals is the need to reduce the uncertainty and improve confidence in modeling results. New characterization efforts are underway, and results from the first year of a three-year well drilling plan are presented.

## INTRODUCTION

From 1951 through 1992 828 underground nuclear tests were detonated in shafts and tunnels at the Department of Energy (DOE) National Nuclear Security Administration (NNSA) Nevada Test Site (NTS) [1]. The Underground Test Area (UGTA) Subproject is a DOE Environmental Restoration activity assessing the risk to the public from radionuclide contamination in groundwater produced during this testing. The considerable depth to groundwater in the testing areas (from about 200 m at Frenchman Flat to greater than 600 m at Pahute Mesa) and the large volume of contaminated groundwater extending across hundreds of square kilometers prohibit cost effective remediation with current technology. Flow and contaminant transport models are being developed to evaluate contaminant transport over the 1,000-year regulatory timeframe. The Subproject is implementing an iterative process of characterization and modeling studies guided by sensitivity and uncertainty analysis, and applying pragmatic assessments of the cost and likelihood of reducing uncertainty in the model results. Also included is reliance on monitoring studies to test and confirm model simulations and build confidence so model results can be used in regulatory decisions. The recently revised UGTA strategy, as identified in the updated Federal Facility Agreement and Consent Order, amended February 2008 [2] is designed to achieve closure of corrective action units (CAUs) through a tripartite combination of characterization and modeling, monitoring and institutional control.

## PAHUTE MESA – CONTAMINATION SOURCE AND HYDROGEOLOGIC SETTING

A number of studies have evaluated NTS geology and the groundwater system [for example, 3-9]. Pahute Mesa, a volcanic highland formed on the north flanks of the Timber Mountain caldera complex, was the site of 82 underground nuclear tests that were detonated in volcanic rocks near and below the water table (Fig.1) [1]. The Central and Western Pahute Mesa CAUs encompass Areas 19 and 20 of the NTS, and are hydrogeologically part of a groundwater flow system that extends through Oasis Valley to Death Valley.

The Pahute Mesa modeling domain contains area from the NTS, the U.S. Air Force (Nevada Test and Training Range) and the Bureau of Land Management.

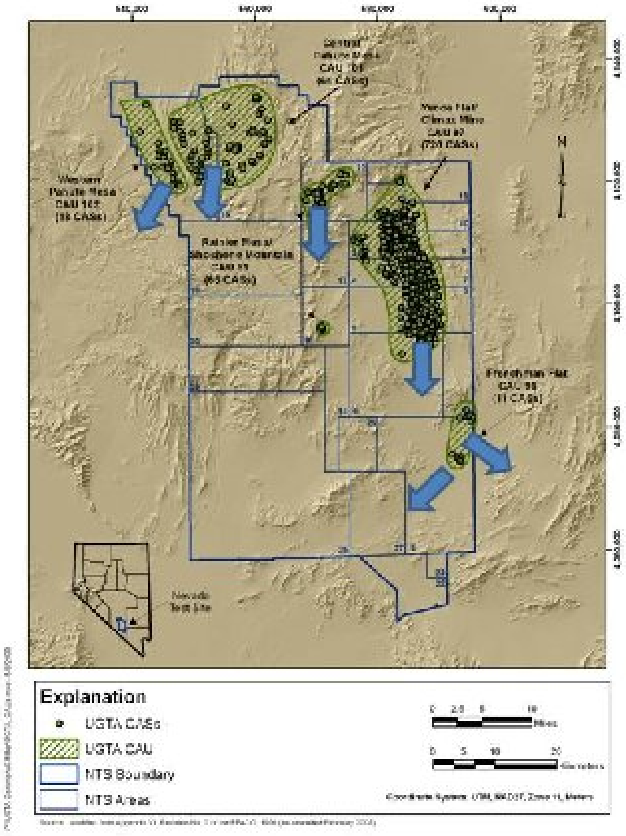

Figure 1. Map of the location of correction action units (green shaded areas) and corrective action sites (small circles) on the Nevada Test Site. The blue arrows show the direction of local groundwater flow based on the regional groundwater flow model and flow and transport studies at individual CAUs (Frenchman Flat [12] and Pahute Mesa [11]). The southeast-directed arrow showing the transport direction in the Frenchman Flat CAU is in the alluvial and volcanic aquifers; regional flow in the carbonate aquifer is to the south and southwest (southwest-directed blue arrow).

Several factors point to the need for understanding contaminant transport away from Pahute Mesa. Pahute Mesa hosted about 10% of the total underground nuclear tests at the NTS, but contains approximately 8.0E+07 Curies (decay corrected to 1992) – approximately 60% of the total NTS inventory [10]. Groundwater flow is primarily through fractured volcanic rocks, and estimated velocities from the Phase I model are higher at Pahute Mesa (up to several hundred m/yr on average) [11] when compared to other NTS CAUs (for example, Frenchman Flat CAU – 0.1-1 m/yr on average) [12]. Residents near Beatty Nevada, about 40 kilometers southwest of Pahute Mesa, are the nearest receptors based on current model estimates of groundwater contaminant migration from the NTS. The size of the inventory, relatively fast groundwater velocity, and down gradient receptors, coupled with the geologic complexity described below, point out the need for focused studies to develop contaminant transport models to quantify uncertainty and increase confidence in the reliability of model results.

The NTS is located in the southern part of the Great Basin, the northern-most sub-province of the Basin and Range physiographic province. As shown in the hydrostratigraphic framework model that was built for Phase I studies [13], Pahute Mesa is geologically complex, encompassing at least six Tertiary-age calderas, many relatively young basins-and-range-style normal faults, and Mesozioc-age thrust faults and intrusive bodies, all superimposed on a basement of highly deformed Proterozoic and Paleozoic sedimentary and metasedimentary rocks. The Tertiary volcanic rocks were deposited from volcanic activity associated with eruptions from multiple volcanic centers in the Southwestern Nevada Volcanic Field (SWNVF) located on or adjacent to the NTS. Many areas are covered by Tertiary and Quaternary surficial deposits. The depth to groundwater in the model area varies from the surface at limited discharge areas in Oasis Valley to more that 670 m below land surface. Perched water occurs locally within the volcanic rocks.

Structural features in the model area include thrust faults (Belted Range and associated smaller imbricate thrust faults), normal faults (northwest- to northeast-striking, high angle faults related to Basin and Range extension), transverse faults and structural zones (generally west- to west-northwest-striking, high angle faults and structural zones oriented traverse to the normal faults, related to caldera formation and Basin and Range extension), one detachment fault (Fluorspar Canyon-Bullfrog Hills fault, a shallow, low-angle fault underlying Tertiary rocks in the southwestern portion of the model area), and multiple calderas. Calderas are complex and hydrogeologically important because of significant heterogeneity in volcanic rocks and the associated structural features that can significantly block or enhance groundwater flow.

Calderas near the Pahute Mesa area formed when voluminous eruptions of pyroclastic rocks rapidly emptied the top of the underlying magma chamber and produced near-circular collapse of the land surface above the chamber to form a large volcanic-tectonic basin. Major thicknesses of intracaldera ash-flow deposits accumulated in these basins during and after eruption, and were subsequently elevated during resurgent doming of the center of the caldera floors. The caldera uplift formed a topographic moat between the resurgent dome and the caldera rim and this moat area was partially infilled by rhyolite domes and associated deposits erupted along the ring fracture zones. Contrasting assemblages of rock types are associated with calderas: caldera-forming eruptions can produce thick ash-flow tuffs cooling units with intercalculated debris-flow deposits inside the caldera edges; later eruptions from sources outside the caldera may deposit volcanic material within the caldera; erosion of the caldera rim can produce thick aprons of alluvial debris within the caldera; rapid mass wasting of larger blocks from the caldera rim can produce caldera collapse breccia deposits; and lakes may also form within caldera depressions resulting in accumulations of lacustrine sediments. All of these rock types have been encountered in drill holes within the Pahute Mesa model area.

While the modern topographic expression of the youngest collapse calderas remains, volcanic and sedimentary deposits of older caldera collapse structures are concealed beneath deposits of younger calderas. There are no collapse caldera structures exposed within the model area. There are several conceptual models of caldera collapse, and two general types are recognized near Pahute Mesa. Piston collapse tends to produce arcuate shaped circular ring-fracture structures (i.e. the Timber Mountain Caldera complex), while collapse along pre-existing linear faults results in polygonal, rectilinear boundaries (i.e. the Silent Canyon Caldera complex).

Stratigraphic and structural data from drilling and geophysical studies have been used to derive insight into the subsurface character of calderas, and chemical and petrographic analysis can be used to determine magma evolution, source areas, and ages [5]. Basin and Range extension and volcanism were synchronous in the SWNVF.

Individually, caldera dimensions, the nature of the structures that form them and the characteristics of the rocks that fill them result in a hydrogeologically diverse environment. The presence of multiple, overlapping, and buried calderas provides a complicated setting for the model domain. Ash-flow tuffs and lavas are composed of zones related to deposition and cooling, such as welding, fracturing and rubble/breccia, and can be overprinted by zones related to secondary alteration and/or hydrothermal activity. Assignment of hydrologic and transport parameters to spatially variable volcanic rocks in a large complex setting with limited data is a Herculean task. The challenge facing the UGTA Subproject is to develop realistic models of flow and transport, quantify the effects of multiple components of uncertainty on flow and transport results, and build confidence in modeling results sufficient to support regulatory decisions.

## PHASE I RESULTS

The first phase of site characterization studies and development of flow and transport models has been completed for the Pahute Mesa CAUs [11]. As displayed in Figure 2, the model results show that transport of radionuclides off of Pahute Mesa may be channeled preferentially into a narrow corridor extending off the southwest Mesa edge, along an area of convergence of two-subparts of the groundwater flow system and across multiple collapse structures of the north part of the Timber Mountain caldera. South of the convergent flow fields the groundwater flow directions bend to the southwest and the transport corridor follows the northwest and west flanks of the Timber Mountain resurgent dome. This area is composed of a variety of volcanic rock types from several calderas that are juxtaposed along caldera ring fracture zones, and locally offset by Basin and Range faults. Flow velocities in the transport corridor may be high from a combination of steep topographic gradients and the convergent flow fields. Phase II activities are focused on understanding why this area appears to control flow and transport paths off Pahute Mesa. Multiple aspects of the modeling remain problematic and will be addressed, including: release processes and transport of radionuclides near the test cavities, multiple permissive alternative models of the geologic framework of structurally complex volcanic rocks, the scaling and model depiction of rock layering and fracture networks in ash-flow and lava units, the connectivity and representation of permeability fields in heterogeneous volcanic rocks, and the importance of colloidal transport of actinides. Many, but not all, transport realizations predict concentrations of radionuclides at sites known from existing wells to be uncontaminated.

Near the end of Phase I flow and transport modeling activities, the UGTA Subproject concluded there was insufficient confidence in the model results to formally calculate contaminant boundaries at a 95% confidence interval based on the Safe Drinking Water Act (SDWA), as required by Federal Facilities Agreement and Consent Order agreements (FFACO). This concern was based on unexpectedly fast migration off Pahute Mesa that might not be consistent with geochemical constraints (namely C-14 analysis) and sensitivity analysis showing strong model dependencies on poorly constrained model parameters. It was recognized that there would be little value in producing a set of contaminant boundary forecasts that may be overly conservative or unrealistic and not defensible because of incompletely constrained parameter values. With regulator concurrence, final Phase I studies were changed to focus on sensitivity studies, evaluating uncertainty in modeling results, and identifying priority data acquisition activities for Phase II.

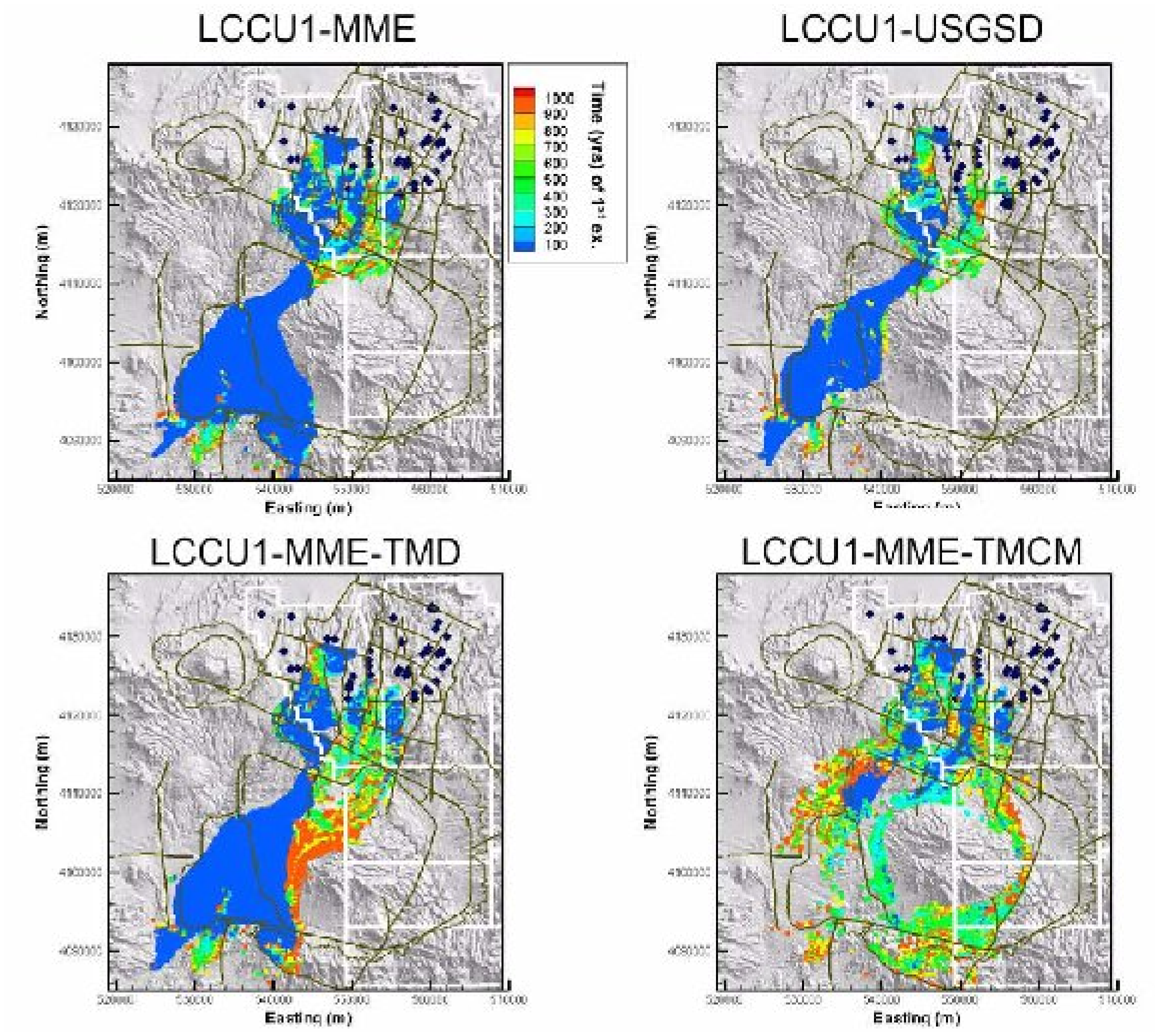

Figure 2. Transport model results (for four alternate transport models in the transport corridor) showing channeling of flow paths off the southwest edge of Pahute Mesa, convergence of parts of the flow system while crossing multiple collapse structures north of the Timber Mountain caldera, and bending to the southwest (and southeast in the lower right plot) around the flanks of the Timber Mountain resurgent dome. The colored lines are probablistic maximum contaminant level (MCL) exceedance maps where color contour per model node indicates the time at which at least 5 percent of the Monte Carlo simulations exceeds a MCL within a 1,000 year interval. [11]

## PHASE II PLANS

Recognizing the need for new data to improve flow and transport models, an UGTA Subproject committee, assisted by the Nevada Site Office (NSO) Citizens Advisory Board (CAB), developed a characterization plan consisting of drilling and aquifer testing [14]. (Other characterization activities were discussed but discarded for various reasons.) Over 20 well locations were identified, and 12 sites were prioritized to address three basic questions identified by the flow and transport models.

1. What are the processes controlling release of radionuclides and how far have radionuclides migrated down gradient from their source areas?
2. What are the hydrostratigraphic and structural features that control convergence of the groundwater flow fields?

3. What is the nature of the preferential fast transport corridor from southwestern Pahute Mesa, through the structurally complex area between the Silent Canyon caldera and the Timber Mountain caldera (referred to as the Bench area) and then west of the Timber Mountain Dome? Is it a dominant feature of the intracaldera volcanic rocks of the Timber Mountain caldera or an artifact of scaling and parameterization of the flow and transport models?

A three-year drilling program is planned for the installation of nine wells, with the expectation that multiple aquifers will be completed with slotted casing at most sites, and completion zones in the cased intervals will be separated after drilling to permit isolated aquifer testing. The strategy is to focus on the transport corridor, where models show focused transport and indicate major contribution to the contaminant boundary. Initial drilling will investigate down gradient but close to the source area, then move down the expected flow pathways. Single well hydrologic tests and groundwater sampling will follow each drilling campaign, and aquifer testing, including multiple well aquifer tests, will occur after all wells are installed. Pressure response is being monitored in nearby wells to help understand hydrologic response during drilling. Data collection should address these general issues:

1. What is the connectivity of the aquifers?
2. What impact do faults have on this connectivity?
3. What is the spatial variability of the data? What scale of model should be applied to best represent flow and transport? Is this scale the same over the entire model domain?

## DATA OBTAINED TO DATE

Three sites (consisting of four wells) were installed during the first drilling campaign, which ran from May to October 2009. The first drill hole, ER-20-7, located on the NTS in southwestern Pahute Mesa, was sited to investigate radionuclide migration about 750 m down gradient from the ER-20-5 well cluster installed in 1995 (Fig. 3). The nearest underground nuclear test to ER-20-7 is located about 960 m to the north-northeast. The ER-20-5 well cluster encountered tritium and plutonium in pumped water samples in the Topopah Spring aquifer (TSA) and a lava flow within the Calico Hills Composite Unit (CHZCM). The plutonium was determined to be from the Benham test conducted in 1968 and located in emplacement hole U-20c, located approximately 1,300 m up gradient of the ER-20-5 wells [15]. ER-20-7 was expected to be contaminated, but it was not known what part of the plume it would intersect – early arrival of contaminants or after breakthrough had passed this location. Additional objectives for ER-20-7 are to characterize the Northern Timber Mountain Moat Structural Zone (NTMMSZ) hydrologic properties and the transition to the Bench area in conjunction with another planned well (ER-EC-11) in the transport corridor. ER-20-7 was drilled to 895 m depth, and the water table was encountered at 616 m depth (predicted at 615 m depth). Two target aquifers were encountered – the deeper TSA was fully saturated as predicted, but the shallower Tiva Canyon Aquifer (TCA), predicted to be above the water table, was found to be partially saturated. Tritium concentrations (in drilling fluids) of about 47,000 to 2,600,000 pCi/L were detected in the TCA, well above the radiological standards of the SDWA (20,000 pCi/L), and required casing off the TCA before drilling continued to the TSA to avoid possible cross contamination of aquifers by the drill hole. Tritium was detected in drilling fluids at concentrations averaging about 20,000,000 pCi/L in the TSA, with a maximum value of about 61,000,000 pCi/L. A single slotted 14.13-cm diameter completion zone was established across the full thickness of the TSA. Small amounts of plutonium were also detected (in drilling fluids) in the TCA (0.04 pCi/L) and in the TSA (0.12 pCi/L). This plutonium has also been fingerprinted to the Benham test. The tritium and plutonium found at the ER-20-5 site and at ER-20-7 indicate the wells are within the model-predicted contaminant plume, and are following plutonium contamination on the NTS from the Benham test over a distance of 1,300 m to ER-20-5 site and then 750 m to E-20-7. The change in contaminated aquifers, from stratigraphically deeper aquifers at the Benham location in the north to the south at ER-20-5 and continuing south to ER-20-7, is attributed to at least two features. First, contaminant transport modeling at the NTS has shown that heat from a nuclear test can establish convection within rubble of the collapse chimney and can transport radionculides to a shallower aquifer above the cavity [16, 17]. The presence of plutonium in shallower and deeper aquifers at the ER-20-5 site supports this concept. Second, structure can juxtapose stratigraphic units and permit contaminant migration from older units to younger units. It is currently believed that a combination of a north-south trending Basin and Range normal fault is responsible for down dropping the Tiva Canyon Formation near ER-20-7 and the NTMMSZ is responsible for juxtaposing older aquifers (on Pahute Mesa) and younger units (on the Bench), which are two features that combined to displaced the section downward on the south into the structural depression of the Timber Mountain caldera.

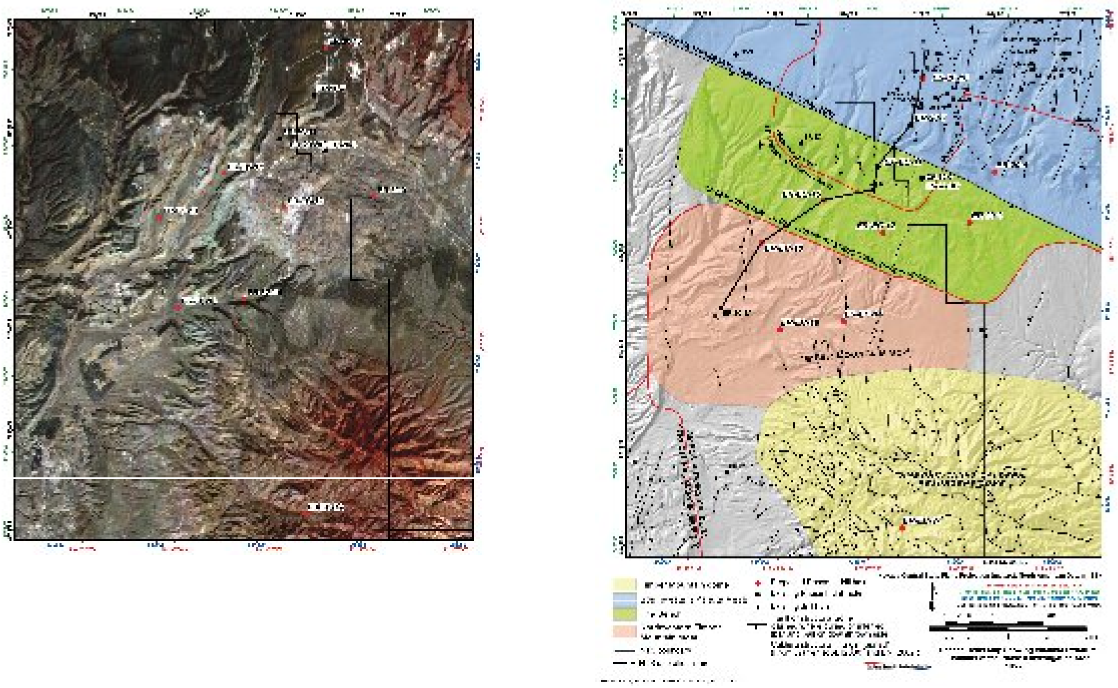

Figure 3. A: Satellite image showing well locations of Phase II wells; B: Location of structural features, faults, underground nuclear test related drill holes, and Phase I and II wells.

The second well to be drilled in 2009 was ER-20-8, located on the NTS but across the NTMMSZ in the Bench area (Fig. 3). It was uncertain whether this well would be contaminated because it was across a major caldera structure down gradient of the source area. The nearest underground nuclear test is just over 3,000 m to the north. The objectives for this well were to investigate the predicted flow paths through the Bench area between the Silent Canyon Caldera Complex and the Timber Mountain Caldera Complex. Another objective was to characterize hydrologic properties of the southward extension of the Boxcar Fault. ER-20-8 was drilled to 1,049 m depth, penetrated the water table at 508 m (predicted at 503 m depth), and encountered three aquifers as predicted. The uppermost aquifer, the Benham aquifer (BA), was partially saturated as predicted, and the TCA and TSA were fully saturated. Tritium was encountered in drilling fluids above the SDWA in a localized zone at 603-619 m depth, below the water table within the BA, and this aquifer was cased off before drilling continued to the next aquifer. No detectable tritium (in drilling fluids) in excess of the SDWA was found in the TCA and TSA. Two slotted 14.13-cm diameter completion zones across the full thicknesses of the TCA and TSA were established, and are isolated by a bridge plug. No other radioactivity was detected in drilling fluids in this well.

Because the contaminated (albeit low) BA was cased off, eliminating the possibility of hydraulic testing and further monitoring of the aquifer, an UGTA guidance team recommended establishing a dedicated BA well at this site. The drill rig was moved about 16 m west of ER-20-8 and ER-20-8 #2 was drilled to 713 m depth. While unplanned costs were incurred in establishing the second well, cost savings were realized from relocating on the same pad, quickly drilling the well in a known setting and not obtaining geophysical logs. No radioactivity above the SDWA was encountered in drilling fluids in the second well and a single slotted 19.36-cm diameter completion zone was established across the saturated portion of the BA.

ER-EC-11 was the last well to be drilled during the 2009 drilling campaign. There was high regulatory and public interest in this well due to its location on the Nevada Test and Training Range just across the NTS boundary. The nearest underground nuclear test is just over 3,150 m to the northeast. ER-EC-11 is approximately 2,150 m down gradient of ER-20-7. The main objective for this well was to investigate radionuclide contamination down gradient of ER-20-7, across the NTMMSZ and into the Bench area. While this well was immediately down gradient of known contamination at the ER-20-5 site and ER-20-7, it was across a major caldera structure, and it was unknown whether this location would be contaminated. Another objective was to characterize the NTMMSZ hydrologic properties in conjunction with ER-20-7. This well was drilled to 1,264 m, deeper than the planned depth of 1,069 m. Additional depth was required to penetrate three aquifers as planned because a thicker-than-predicted Fortymile Canyon confining unit was penetrated high in the hole (above the BA). The water table was encountered at 449.6 m (predicted at 450.2 m). Tritium in drilling fluids not exceeding the SDWA was encountered in the BA, and the aquifer was cased off before drilling to the next aquifer. No detectable tritium (in drilling fluids) was found in the TCA and the TSA. Two slotted 19.13-cm diameter completion zones across the full thicknesses of the TCA and TSA were established, and are isolated by a bridge plug. Additional radioactivity analyses are not yet complete. Current thoughts are that a dedicated BA well will need to be established at this site, similar to the ER-20-8 site.

## CONCLUSIONS TO DATE

1. Four wells were established in the first of three planned drilling campaigns. This included construction of an unplanned well. The total actual depth of these wells was 3,920 m compared to the planned 3,718 m (202 m more than planned). Drilling took 113 days compared to the planned 96 days. On average it cost approximately $5.3 million to drill these three deep characterization wells. The average cost does not include ER-EC-8 #2, which was shallower and did not include all activities at a typical deep characterization well.
2. The geologic structure in this area of overlapping calderas is complex. Some stratigraphic predictions are on target while others are not. Water level predictions have been on target. Confidence in predictions at new wells located farther from known constraints are more uncertain, and collecting new information will be valuable in providing hydrogeologic data to improve confidence in our models.
3. Newly acquired data have offered confirming evidence for the conceptual model of radionuclide transport: contamination moves off Pahute Mesa in the TSA and CHZCM (at the ER-20-5 site) and merges down gradient with the juxtaposed TSA, TCA, and BA, where these units are connected by faults (ER-20-7, the ER-20-8 site, and ER-EC-11). This means contaminates migrating down gradient of Pahute Mesa move to stratigraphically higher units as caldera structure down drops the volcanic units to the south. The BA is hypothesized to be the main aquifer of concern at the leading edge of the contaminant plume.

Figure 4 shows a northeast (right side) to southwest (left side) cross section from southern Pahute Mesa through the Bench and Timber Mountain Moat areas to support the radionuclide migration conceptual model described above. The figure includes underground nuclear tests, selected Phase I wells, Phase II well ER-20-7, selected Phase II planned wells, stratigraphy, and topographic, and structural features.

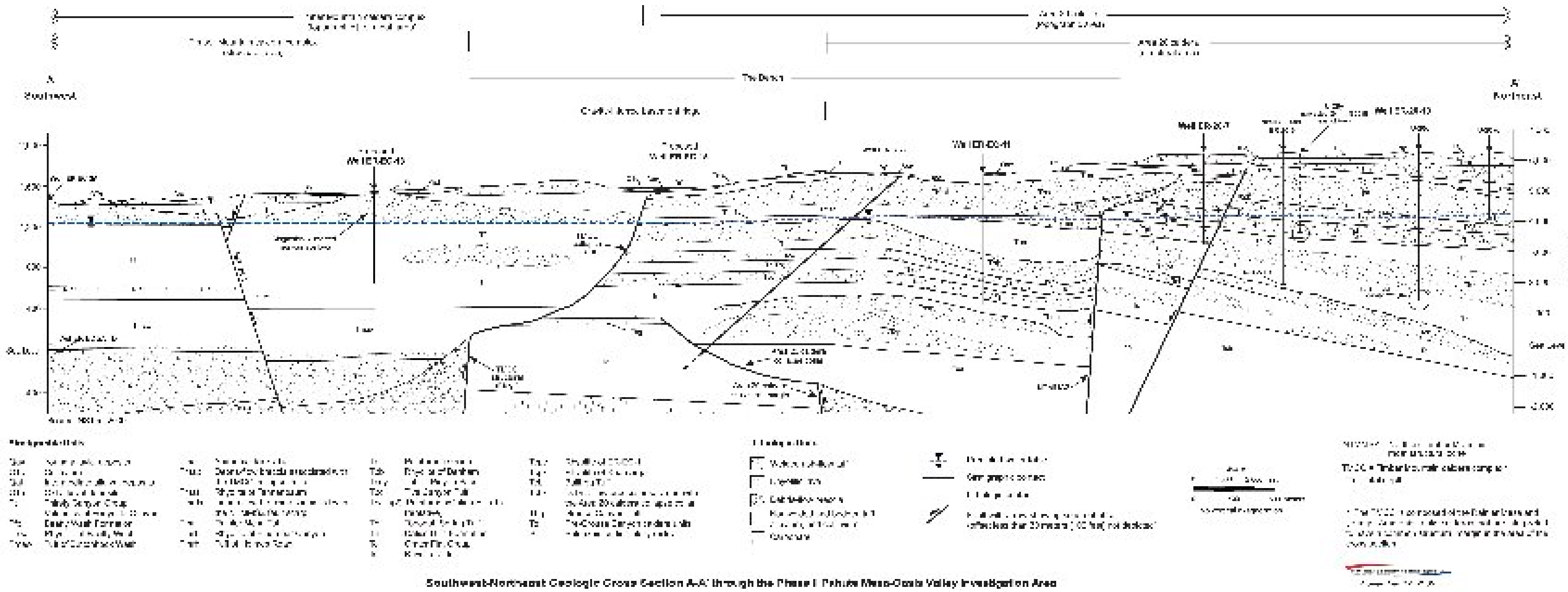

Figure 4. A cross section from southern Pahute Mesa (right side) through the Bench and Timber Mountain Moat areas, as located on Fig. 3B Features to note are: **underground nuclear tests** (Goldstone in U-20ao, Benham in U-20c, and Tybo in U-20y); **selected Phase I wells** (the ER-20-5 site, ER-EC-6 and ER-EC-2A); **Phase II wells drilled to date** (only ER-20-7 is shown on this cross section); **selected Phase II planned wells** (ER-20-10, ER-EC-15 and ER-EC-13); **stratigraphy** (layered, dipping, and juxtaposed across faults); **topographic features (**the Area 20 caldera and the Timber Mountain caldera complex); **structural features** (the Area 20 caldera, the Bench, the gravity inferred ridge separating the Area 20 caldera from the Timber Mountain caldera complex, and the Timber Mountain complex caldera).

## REFERENCES

1. US DOE (U.S. DEPARTMENT OF ENERGY), "United States Nuclear Tests July 1945 through September 1992", DOE/NV--209 Rev 15, U.S. Department of Energy, Nevada Operations Office (2000).
2. FFACO, FEDERAL FACILITY AGREEMENT AND CONSENT ORDER, Agreed to by the U.S. Department of Energy, Environmental Management; the U.S. Department of Defense; U.S. Department of Energy, Legacy Management; and the State of Nevada, as amended February 2008.
3. R.K. BLANKENNAGEL and J.E.WEIR, JR., "Geohydrology of the Eastern part of Pahute Mesa, Nevada Test Site, Nye County, Nevada, Professional Paper 712-B, U.S. Geological Survey (1975).
4. I.J. WINOGRAD and W. THORDARSON, "Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, with Special Reference to the Nevada Test Site", Professional Paper 712-C, U.S. Geological Survey (1975).
5. D.A. SAWYER, R.J. FLECK, M.A. LANPHERE, R.G. WARREN, D.E. BROXTON, and M.R. HUDSON, "Episodic Caldera Volcanism in the Miocene Southwestern Nevada Volcanic Field: Revised stratigraphic framework, 40Ar/39 geochronology, and implications for magmatism and extension", Geologic Society of America Bulletin, **106**, p.1304-1318 (1994).
6. R.J. LACZNIAK, J.C. COLE, D.A. SAWYER, and D.A. TRUDEAU, "Summary of Hydrogeologic Controls on Ground-Water Flow at the Nevada Test Site, Nye County, Nevada", Water Investigations Report 96-4109, U.S. Geological Survey (1996).
7. R.R. WAHL, D.A. SAWYER, S.A. MINOR, M.D. CARR, J.C. COLE, W.C. SWADLEY, R.J. LACZNICK, R.G. WARREN, K.S. GREEN, and C.M. ENGLE, "Digital Geologic map Database of the Nevada Test Site Area, Nevada", OFR-97-140, U.S. Geological Survey (1997).
8. V.J.S. GRAUCH, D.A. SAWYER, C.J FRIDRICH, and M.R. HUDSON, "Geophysical Framework of the Southwest Nevada Volcanic Field and Hydrogeologic Implications", Professional Paper 1608, U.S. Geological Survey (1999).
9. W.R. BELCHER, J.B. BLAINEY, F.A. D'AGNESE, C.C. FAUNT, M.C. HILL, R.J. LACZNIAK, B.M. O'BRIEN, C.J. POTTER, H.M. PUTMAN, C.A. SAN JUAN, and D.S. SWEETKIND, "Death Valley Regional Model Ground-Water Flow System, Nevada and California – Hydrogeologic Framework and Transient Ground-Water Flow Model", Scientific Investigations Report 2004-5205, U.S. Geological Survey (2004).
10. S.M. BOWEN, D.L. FINNEGAN, J.L. THOMPSON, C.M. MILLER, P.L. BACA, L.F. OLIVAS, C.G. GEOFFRION, D.K. SMITH, W. GOISHI, B.K. ESSER, J.W. MEADOWS, N. NAMBOODIRI, and J.F. WILD, "Nevada Test Site Radionuclide Inventory, 1951-1992", LA-13859-MS, Los Alamos National Laboratory (2001).
11. SNJV (STOLLER NAVARRO JOINT VENTURE), "Phase I Transport Model of Corrective Action Units 101 and 102: Central and Western Pahute Mesa, Nevada Test Site, Nye County, Nevada", S-N/99205-111, Stoller Navarro Joint Venture (2009).
12. SNJV (STOLLER NAVARRO JOINT VENTURE), "Phase II Transport Model of Corrective Action Units 98: Frenchman Flat, Nevada Test Site, Nye County, Nevada", S-N/99205-122, Stoller Navarro Joint Venture (2009).
13. BECHTEL NEVADA, "A Hydrostratigraphic Model and Alternatives for the Groundwater Flow and Contaminant Transport Model of Corrective Action Units 101 and 102; Central and Western Pahute Mesa, Nye County, Nevada", DOE/NV/11718—706, Bechtel Nevada (2002).
14. US DOE (DEPARTMENT OF ENERGY), "Phase II Corrective Action Plan for Corrective Action Units 101 and 102: Central and Western Pahute Mesa, Nevada Test Site, Nye County, Nevada", U.S. Department of Energy, Nevada Operations Office (2009).
15. A.B. KERSTING, D.W. EFURD, D.L. FINNEGAN, D.J. ROKOP, D.K. SMITH, and J.L. THOMPSON, "Migration of Plutonium in Groundwater at the Nevada Test Site", Nature, **397**, p.56-59 (1999).

16. G.A. PAWLOSKI, A.F.B TOMPSON, and S.F. CARLE, Editors, "Evaluation of the Hydrologic Source Term from Underground Nuclear Tests on Pahute Mesa at the Nevada Test Site: The Cheshire Test", UCRL-ID-147023, Lawrence Livermore National Laboratory (2001).
17. A.L. WOLFSBERG, L. GLASCOE, G. LU, A. OLSON, P. LICHTNER, M. MCGRAW, and T. CHERRY, "Tybo/Benham Model Analysis of Groundwater Flow and Radionuclide Migration from an Underground Nuclear Test in Southwestern Pahute Mesa, NTS", LA-UR-012924, Los Alamos National Laboratory (2001).

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work supports the Underground Test Area Project of the United States Department of Energy, National Nuclear Security Administration, Nevada Site Office.

DOE/NV—1342

LLNL-CONF-422250