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Moisture Monitoring at Area G, Technical Area 54, Los Alamos National Laboratory

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Acronyms and Abbreviations

16s	16-second
amsl	above mean sea level
bgs	below ground surface
CA	composite analysis
CPN	Campbell Pacific Nuclear
CSI	Campbell Scientific Inc.
CT	crushed tuff
DOE	Department of Energy
ET	evapotranspiration
HDP	heat dissipation probe
LANL	Los Alamos National Laboratory
LLW	low-level radioactive waste
MDA	Material Disposal Area
msl	mean sea level
NMED	New Mexico Environment Department
P38X	Pit 38-Extension
PA	performance assessment
PCB	polychlorinated biphenyl
PET	potential evapotranspiration
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RSS	radioactive sealed source
SOP	standard operating procedure
SZ	saturated zone
TA	Technical Area
TDR	time-domain reflectometry
USGS	U.S. Geological Survey

UZ	unsaturated zone
VPN	vapor-phase notch
VWC	volumetric water content

Executive Summary

Hydrological characterization and moisture monitoring activities provide data required for evaluating the transport of subsurface contaminants in the unsaturated and saturated zones beneath Area G, and for the Area G Performance Assessment and Composite Analysis. These activities have been ongoing at Area G, Technical Area 54 of the Los Alamos National Laboratory since waste disposal operations began in 1957.

This report summarizes the hydrological characterization and moisture monitoring activities conducted at Area G. It includes moisture monitoring data collected from 1986 through 2014 from numerous boreholes and access tubes with neutron moisture meters, as well as data collected by automated dataloggers for water content measurement sensors installed in a waste disposal pit cover, and buried beneath the floor of a waste disposal pit.

This report is an update of the Jennings and French (2009) moisture monitoring report and includes all data from Jennings and French (2009) and the Draft 2010 Addendum moisture monitoring report (Jennings and French, 2010). For this updated report, all neutron logging data, including neutron probe calibrations, were investigated for quality and pedigree. Some data have been recalculated using more defensible calibration data. Therefore, some water content profiles are different from those in the Jennings and French (2009) report.

Monitoring and characterization data generally indicate that some areas of the Area G vadose zone are consistent with undisturbed conditions, with water contents of less than five percent by volume in the top two layers of the Bandelier tuff at Area G. These data also indicate that other areas of the vadose zone are affected by waste disposal activities that have been ongoing at Area G since 1957, a period of nearly 60 years. In some areas, water content profiles indicate increases in water content to depths of tens of meters, especially in areas covered by asphalt and structures.

Introduction

This report provides a comprehensive summary of moisture monitoring and other hydrological data collection activities conducted at Area G, Technical Area 54 (TA-54), at Los Alamos National Laboratory (LANL). Moisture monitoring has been conducted in and around operational and closed waste disposal units, within interim waste pit covers composed of crushed tuff, and in surrounding deeper intact tuff. In general, the objectives of moisture monitoring are to:

1) provide data used to evaluate the transport of subsurface contaminants beneath Area G as part of the Area G Performance Assessment and Composite Analysis;
2) identify trends that could indicate moisture movement and associated contaminant transport over time in order to mitigate the cause of those trends;
3) evaluate the performance of interim waste disposal pit evapotranspiration (ET) covers; and to
4) evaluate the degree of wetting that occurs beneath waste pits during open operational periods.

In the following sections, this report includes a general site description including descriptions of the stratigraphy and hydrogeology beneath Area G. This is followed by an annotated bibliography of relevant Area G studies that discuss moisture or subsurface transport data, and a summary of all moisture monitoring data collected at Area G including details of neutron probe calibrations. The report includes a summary section, and a recommendations section that lists future work that could be conducted to improve the quality and defensibility of the moisture monitoring program at Area G.

All neutron logging data were thoroughly evaluated for quality, and for pedigree (original source datasets), if those data were available. Data files were acquired from three sources: 1) the Project repository from Northwind Inc. (former subcontractor); 2) data files for the Medusa boreholes from Steve McLin (retired LANL employee); and 3) data files maintained by Dennis Newell (former LANL employee). All data files acquired and developed for this report are summarized in Appendix A of this report, including a figure showing the file directory structure of all data files.

Throughout this report, the use of “water content” and “moisture content” are synonymous. The use of the term “moisture monitoring” is included in this report, notably in the title, for continuity with previous reports. However, the term “water content” is primarily used in this updated report. Unless noted, water contents are volumetric (by volume) rather than gravimetric (by weight). Although this report includes both metric and/or English units, most units are English in order to preserve original source data values.

Site Description

Area G is located on Mesita del Buey in the east-central portion of the Laboratory at TA-54 (Figure 1). Mesita del Buey (and the majority of TA-54) was identified in 1956 by the United States Geological Survey (USGS, 1956) as a prospective radioactive waste disposal site because of its favorable hydrogeologic properties. Area G is one of four disposal areas situated within TA-54; the other three are MDAs H, J, and L. Area G includes both MDA G and Zone 4 expansion area (Figure 2). All waste disposal at Area G is currently confined to MDA G.

MDA G is located on the eastern portion of Mesita del Buey, a 30 to 43 m (100 to 140 feet [ft]) high finger-shaped mesa that trends northwest-southeast. The elevation of this portion of Mesita del Buey ranges from 2,198 to 2,219 m (7,210 to 7,280 ft) above mean sea level (amsl). The mesa varies in width from about 150 to 300 m (500 to 1,000 ft) and is bounded by Cañada del Buey to the north and Pajarito Canyon to the south. The topography of Area G is relatively flat and narrow, with steep sides that drain into Cañada del Buey and Pajarito Canyon. The north-facing slope of the mesa has a gentler gradient than the south-facing slope, which is almost vertical near the rim and becomes less steep toward the canyon floor.

MDA G is a 65-acre fenced area consisting of asphalt-paved roads and storage areas, graded roads, buildings, utilities, storm-water drainages, and below-ground waste disposal or waste storage units (pits, shafts, and trenches). The site has served as the primary low-level radioactive waste (LLW) disposal site for the Laboratory since 1959 and has been used for the disposal and temporary storage of low-level and radioactive waste and certain radioactively contaminated waste, asbestos-contaminated material, and polychlorinated biphenyls (PCBs).

The disposal capacity of MDA G is nearly exhausted and the future disposal of waste is planned to occur within pits and shafts of the Area G Zone 4 expansion area (Figure 2) (French et al., 2008). The current disposal forecast calls for disposal operations within MDA G pits to cease in 2015; disposal operations in MDA G shafts will cease 5 years later, in 2020. After these dates, the respective disposal operations will shift to the expansion area. It is assumed that disposal operations in Zone 4 will continue through 2044. Based on this assumption, final closure of Area G is assumed to be completed by 2046 (French et al., 2008, p. 1-8).

The construction and use of disposal units at MDA G has progressed generally from east to west. The result has been the construction of 35 disposal pits and more than 200 shafts (Figure 3). The surface of MDA G is regularly modified to accommodate ongoing waste storage and management operations; only a limited portion of MDA G is undisturbed with respect to vegetation. Portions of the disposal units at MDA G are covered with asphalt or concrete to enable ongoing waste management activities. Surface runoff from the site is controlled and discharged into Cañada del Buey and Pajarito Canyon. Storm water and sediment monitoring stations are distributed throughout TA-54 and in drainages leading to the canyons.

The disposal pits, trenches, and shafts at MDA G are located within unit Qbt 2 (cap rock) and unit Qbt 1v of the Tshirege Member of the Bandelier Tuff. The depth of the regional aquifer is 269 m (883 ft) below ground surface (bgs) at monitoring well R-22, located about 30 m (100 ft) to the east of the Area G fence line (LANL, 2002).

The moisture contents of soils and geologic strata at Area G are determined by myriad factors related to the movement of surface water and groundwater within, beneath, and adjacent to the facility. As such, the monitoring of moisture contents provides insight into the performance of the facility with respect to the groundwater pathway. With this in mind, numerous angled and vertical boreholes have been installed at MDA G as part of previous and ongoing subsurface investigation and characterization activities. Vertical (and some horizontal) moisture monitoring access tubes have also been installed in many of the MDA G disposal pits to monitor moisture trends within the waste zone.

Stratigraphy

The upper stratigraphic units underlying Area G include the Bandelier Tuff and the Cerros del Rio basalts. The following sections describe these units to an approximate depth of 358 m (1,173 ft), as measured at well R-22. More detailed information on the geology of the area is available in the MDA G investigation work plan, investigation report, and corrective measures evaluation report (LANL, 2004; LANL, 2005; LANL 2011).

Figure 4 provides a generalized profile of the stratigraphic units of the Bandelier Tuff in the vicinity of Area G. A description of the stratigraphy and the hydrogeologic conditions at the disposal site is provided below.

Tshirege Member

The Tshirege Member of the Bandelier Tuff is a compound-cooling unit that resulted from several successive ash-flow deposits separated by periods of inactivity, which allowed for partial cooling of each unit. Properties related to water flow and contaminant migration (e.g., density, porosity, degree of welding, fracture content, and mineralogy) vary both vertically and laterally as a result of localized emplacement temperature, thickness, gas content, and composition.

Welded (i.e., compacted) tuffs generally exhibit lower porosity and matrix hydraulic conductivity, and are more fractured than nonwelded tuffs.

Tshirege Member Unit Qbt 2. Unit Qbt 2 of the Tshirege Member, a competent, resistant unit that forms the surface of Mesita del Buey, varies in thickness from about 11 to 12 m (35 to 40 ft). Where exposed, unit Qbt 2 forms nearly vertical cliffs on the sides of the mesa. The unit is a moderately welded ash-flow tuff composed of crystal-rich, devitrified pumice fragments in a matrix of ash, shards, and phenocrysts (primarily potassium feldspar [sanidine] and quartz).

Unit Qbt 2 is extensively fractured as a consequence of contraction during post-depositional cooling. The cooling-joint fractures are visible on mesa edges and the walls of pits. On average, the fractures in unit Qbt 2 are nearly vertical. Mean spacing between fractures ranges from 0.6 to 0.8 m (1.9 to 2.6 ft), and the fracture width ranges from less than 0.08 to 1.3 cm (0.03 to 0.51 in) with a median width of 0.31 cm (0.12 in). The fractures are typically filled with clays to a depth of about 3 m (10 ft); smectites are the dominant clay minerals present. Smectites are known for their tendency to swell when water is present and for their ability to strongly bind certain elements, both of which have implications for transport in fractures. Opal and calcite may occur throughout the fractured length, usually in the presence of tree and plant roots (live and decomposed); the presence of both minerals and roots indicates some water at depth in fractures. Most fractures dissipate at the bottom of unit Qbt 2.

A series of, discontinuous, crystal-rich, fine- to coarse-grained surge deposits that are less than 9.9 cm (3.9 inches [in]) thick mark the base of unit Qbt 2. Bedding structures are often observed in these deposits.

Tshirege Member Unit Qbt 1v. Tshirege Member unit Qbt 1v is a vapor-phase-altered cooling unit that underlies unit Qbt 2. This unit forms sloping outcrops, which contrast with the near-vertical cliffs of unit Qbt 2. Unit Qbt 1v is further divided into units Qbt 1v-u and Qbt 1v-c.

- Unit Qbt 1v-u. This uppermost portion of unit Qbt 1v (the "u" signifies upper) consists of devitrified and vapor-phase-altered ash-fall and ash-flow tuff, the thickness of which varies from about 18 to 23 m (60 to 75 ft). The base of unit Qbt 1v-u is unconsolidated but the unit becomes moderately welded near the overlying unit Qbt 2. Only the more prominent cooling fractures that originate in unit Qbt 2 continue into the welded upper section of unit Qbt 1v-u; none of these fractures continue into the less consolidated lower section.
- Unit Qbt 1v-c. Unit Qbt 1v-c consists of poorly welded, devitrified tuff at the top and bottom and a more welded interior; the unit is approximately 8 m (25 ft) thick. The "c" in the name of the unit stands for colonnade, derived from the columnar jointing visible in cliffs formed from this unit.

Tshirege Member Unit Qbt 1g. The basal contact of unit Qbt 1v-c is marked by a rapid change (within 0.2 vertical m [0.7 ft]) from the devitrified (crystallized) matrix of the overlying unit to the vitric (glassy) matrix of the underlying unit Qbt 1g. The vitric pumices in unit Qbt 1g stand out in relief on weathered outcrops, whereas the devitrified pumices above are eroded away. In outcrop, the contact interval forms a prominent erosional recess termed the vapor-phase notch (VPN). No depositional break is associated with the VPN. Rather, the abrupt transition between units is indicative of the devitrification that occurred in the hot interior of Unit Qbt 1v-c after emplacement.

Unit Qbt 1g is a vitric, pumiceous, nonwelded ash-flow tuff about 43 m (140 ft) thick. Few fractures are observed in the visible outcrops of this unit, and the weathered cliff faces have a distinctive Swiss-cheese appearance because of the softness of the tuff. The uppermost 1.5 to 6 m (5 to 20 ft) of unit Qbt 1g are iron-stained and slightly welded. This portion of unit Qbt 1g is resistant to erosion, which accentuates the VPN in outcrop. A distinctive pumice-poor surge deposit forms the base of unit Qbt 1g.

Tsankawi Pumice Bed

The Tsankawi Pumice Bed is the basal air-fall deposit of the Tshirege Member. This thin bed of gravel-sized vitric pumice has a thickness of about 0.9 m (3 ft).

Cerro Toledo Interval

The Cerro Toledo interval (Qct) consists of thin beds of tuffaceous sandstones, paleosols, siltstones, ash, and pumice falls that separate the Tshirege and Otowi Members of the Bandelier Tuff. The Cerro Toledo interval also includes localized gravel- and cobble-rich fluvial deposits predominantly derived from the intermediate composition lavas of the Jemez Mountains west of the Pajarito Plateau. This interval varies from about 4.5 to 9 m (15 to 30 ft) thick.

Otowi Member

The tuffs that comprise the Otowi Member (Qbo) of the Bandelier Tuff are about 24 m (80 ft) thick and represent a massive, nonwelded, pumice-rich, and mostly vitric ash flow. The pumices are fully inflated and support tubular structures that have not collapsed as a result of welding. The matrix is an unsorted mix of glass shards, phenocrysts, perlite clasts, and minute broken pumice fragments.

Guaje Pumice Bed

The Guaje Pumice Bed is the basal air-fall deposit of the Otowi Member. The thickness of the unit is about 3 m (10 ft). The pumice bed is nonwelded but brittle and pumice tubes are partially filled with silica cement.

Cerros del Rio Basalts

In the vicinity of TA-54, the Cerros del Rio basalts (Tb4) lie directly beneath the Otowi Member of the Bandelier Tuff. The basalts are about 194 m (636 ft) thick in characterization well R-32, which is located about 0.5 km (0.3 mi) west-southwest of MDA G; in monitoring well R-22, located less than 0.25 km (0.15 mi) east of MDA G, the basalts are about 611 m (983 ft) thick. In both wells, the basalts serve as the host rock for the regional aquifer. Local borehole cores show that the basalts consist of both angular rubble and dense, fractured masses, with zones of moderately to very porous lavas. Deeper drilling at R-22 showed a wide variety of lithologies within the basalts, including massive flows, interflow rubble or scoria zones, sediments, and paleosols.

Hydrogeology

The hydrology of the Pajarito Plateau is defined by a complex interaction of geography, geology, and climate and paleoclimate (Birdsell et al., 2005). Mesas are generally dry, both at the surface and within the subsurface; prior to 1957, Mesita del Buey was one of the drier mesas at the Laboratory. Canyons range from wet to relatively dry; the wettest canyons originate in the mountains, and contain continuous streams and perennial groundwater in the canyon-bottom alluvium. Dry canyons generally originate on the plateau, and have only occasional stream flow and generally lack alluvial groundwater. Pajarito Canyon to the south of Mesita del Buey is one of the wetter canyons at LANL, while Cañada del Buey north of the mesa is one of the driest. This section discusses the occurrence, distribution, and movement of groundwater at LANL, and more specifically, in the vicinity of Area G.

Precipitation

Area G receives approximately 33 cm (13 in) of precipitation annually. A 22-year record (1993-2014) measured at the TA-54 meteorology station is shown in Figure 5. This record shows the drought period in 2001-2003 that resulted in a massive die-off of local piñon pine populations. This record also shows that 2012 and 2014 were relatively dry years. In September 2013, a 1,000-year storm delivered 170 mm (6.7 in) to Area G in six days and caused widespread flooding (and catastrophic flooding in Colorado). For the month of September 2013, Area G received a total of 195 mm (7.7 in) of precipitation. Despite this precipitation event, Area G received only slightly above-average rainfall for 2013.

Infiltration

The vast majority of the precipitation that falls on Area G is lost through evaporation and transpiration (or the combined process of ET) under natural conditions, resulting in low infiltration rates. Newman et al. (2005) estimated long-term moisture fluxes based on pore-water chloride concentrations and found fluxes for the Area G pit covers and the piñon-juniper woodland located in the Zone 4 expansion area were generally between 3 to 9 mm/yr, or about 1 to 3 percent of average annual current-day precipitation.

Relatively small volumes of water infiltrate into the mesas at LANL under natural conditions because of low rainfall, runoff into canyons, high evaporation, and efficient water use by vegetation. Air circulates through the mesas because of the relatively dry pore spaces and the topographic relief, leading to evaporation from the tops and sides of the mesas. Air circulation may be driven by temperature variations, barometric pumping, or surface winds. This circulation process promotes atmospheric evaporation, which may extend deep within the mesa (especially in fractured or permeable rock) and further inhibit downward liquid-water flow (Turin, 1995).

Daily potential ET (PET) generally ranges from greater than 10 mm in summer, to less than 1 mm in winter. The average annual PET calculated with meteorology data measured at TA-54 is about 174 cm (68 in) (Levitt 2008), or about five times the average annual precipitation. Figure 6 shows daily PET calculated from meteorology data at TA-54. Despite the large ratio of PET to precipitation, winter rains and snowmelt can result in substantial amounts of infiltration, depending on several factors such as topography and antecedent moisture. Turin (1995) discusses a field experiment at TA-73 that measured rapid infiltration from snowmelt to depths of 15 to 30 m (50 to 100 ft).

While episodic infiltration can rapidly reach great depths in some areas of LANL, under the mesa top conditions of Area G, infiltration through the shallow soils and into the cap rock is partially inhibited by the moderately-welded cap rock (Unit 2) of Bandelier tuff as evidenced by plant roots that have been observed to spread along the soil-bedrock interface in areas where shallow soils were removed. However, plant roots are also observed to depths of tens of meters below ground surface within most exposed fractures when pits are newly excavated (Turin, 1995; Krier et al., 1997; Reneau and Vaniman, 1998). The presence of these roots suggests that some episodic infiltration occurs in fractures of the Bandelier tuff, probably when saturated or near-saturated conditions occur at the soil-bedrock interface.

Infiltration into and through open and closed disposal units have been investigated in numerous studies, most recently by LANL (2008), Levitt (2008, 2011), and French et al. (2013). Infiltration in interim ET covers composed of crushed tuff overlying filled waste pits has been investigated by LANL (2008, Appendix E) for MDA A and infiltration in the ET cover planned for Area G, composed of a mixture of crushed tuff and bentonite (a.k.a. CT-clay), has been investigated by Levitt (2008). The range of infiltration calculated in Levitt (2008) using HYDRUS-1D (Šimùnek et al., 2005) was used as the infiltration boundary condition for the full unsaturated zone (UZ) and saturated zone (SZ) models using the flow and transport code FEHM (Zyvoloski et al., 2007) that are used as input to the 2008 PA. As a result of the very low infiltration calculated by Levitt (2008) for the CT-clay ET cover (e.g. 0.025 mm/yr), there is no groundwater pathway for dose within the regulatory period in the 2008 PA (French et al., 2008).

Increased infiltration has long been known to occur while disposal pits are open (referred to as "transient infiltration"). Most pits at Area G were open for periods of less than five years; however, some pits were left open for much longer periods such as Pits 37 and 39 which were open for 21 and 16 years, respectively. During the period that pits are open, they are subject to increased infiltration from runoff from surrounding surfaces such as access ramps, from lack of soil storage for subsequent evaporation (unless waste layers are covered with CT), lack of transpiration due to lack of vegetation, and reduced evaporation due to shading and wind blocking from pit walls. A portion of Pit 38 had exposed waste containers for several years without a CT cover; nearly all the precipitation that fell on this portion of the pit may have infiltrated between the waste containers. Concerns over transient infiltration have been raised by stakeholder groups (e.g. Northern New Mexico Citizens Advisory Board [NNMCAB, 2009]). Simulations of infiltration were conducted by Levitt (2011) to investigate transient infiltration in open pits.

Infiltration can also increase as a result of dust suppression activities, and from decontamination activities. A Special Analysis (SA) was conducted to evaluate the impact from water applications to Pits 37 and 38 as a result of decontamination activities (French et al., 2013). Numerical modeling using HYDRUS-2D (Šimùnek et al., 2007) was conducted to simulate infiltration through the floors of Pits 37 and 38. Those results were then used to simulate flow through the UZ and the SZ with FEHM (Zyvoloski et al., 2007). The result of all calculations in the SA were that although calculated dose was well below any regulatory limits, breakthrough (at a compliance water well) occurred in less than 1,000 years as a result of the decontamination water application.

Increased infiltration at Area G can also occur in areas covered by asphalt, structures, and roads. Roads are frequently sprayed with water for dust control, most of which evaporates, but some may result in infiltration. And most roads at Area G have a runoff ditch adjacent to them that can contribute to enhanced infiltration. The occurrence of roads, asphalt paving, and structures overlying closed waste pits can be seen in Figure 7.

Neeper et al. (1996), Rofer et al. (1997), and Levitt et al. (2005) describe the effects of an asphalt cover over MDA AB at TA-49 at LANL. These studies conclude that the asphalt cover causes increased infiltration by all but eliminating ET, but allowing runoff and focused infiltration through cracks in the asphalt. Condensation of water vapor beneath the asphalt may have also resulted in increased water contents. After asphalt cracks were sealed, new cracking was observed to occur in less than two years (Rofer et al., 1997). Many parts of Area G have been covered with asphalt and structures for decades, and their eventual removal will result in decreased water contents and infiltration fluxes in the future.

Vadose Zone

The region beneath the ground surface and above the regional aquifer is called the vadose zone, or unsaturated zone (UZ). Precipitation is the source of moisture in the vadose zone, and any precipitation not removed through the processes of runoff and ET results in net infiltration beneath the root zone. This soil moisture tends to move vertically through the vadose zone towards the water table. As moisture migrates, this recharge is influenced by the properties of the vadose zone hydrogeology. Migration rates are generally low (e.g., on the order of mm/yr) because PET is so much greater than precipitation at Area G.

Two geologic properties of the Bandelier Tuff that influence fluid flow in the vadose zone are the degree of welding and devitrification, both of which were determined by the presence of residual gases and high temperatures when the tuff was deposited. Because different tuff units were deposited at different temperatures and because individual units were laid out in variable thicknesses over different landscapes, cooling was not uniform. Consequently, welding varies spatially both between and within separate depositional layers. Welded tuffs tend to be more fractured than non-welded tuffs.

Several competing effects determine moisture content and fluid flux in welded, devitrified tuff. Although water moves slowly through the unsaturated tuff matrix, it can move relatively rapidly through fractures if nearly saturated conditions exist (Hollis et al., 1997). Generally, field moisture contents in the upper

30 m (100 ft) of tuff at Area G are less than 5 percent by volume in areas undisturbed by disposal pits, trenches, and shafts and, most notably, asphalt covers. Near-surface moisture contents of up to 25 percent have been measured beneath large asphalt surfaces because of the absence of plant transpiration and the suppression of atmospheric venting (Krier et al., 1997).

A modeling study for Area G indicated that fractures become wet and conduct water only when substantial infiltration occurs at the ground surface. If the water source stops, the dominant process reverts to matrix flow. In addition, when fractures terminate at contacts between stratigraphic subunits such as the Cerro Toledo interval, or if fractures are filled, then water traveling through the fractures is also absorbed into the tuff matrix (Soll and Birdsell, 1998). Even when the tuff matrix is saturated, most of the deeper fractures beneath Area G are dry. In addition, Robinson et al. (2005) describe simulations of an injection test at TA-50 and conclude that the simulations with and without the presence of fractures yield similar results. The test was conducted in units Qbt 3 and Qbt 2 of the Bandelier tuff, so they are relevant to Area G.

Deep infiltration at Area G may or may not result in recharge of the regional aquifer. The presence of cooling joints or fractures within some units of the Tshirege Member of the Bandelier Tuff may dry out portions of the mesa. The driest zone within the mesa generally occurs within the lower portion of Tshirege unit Qbt 2 and the upper part of unit Qbt 1v, a region that coincides with fractures (Krier et al., 1997). Rogers et al. (1996) note that this is also a zone of high matric suction and a hydraulic head minimum, suggesting that moisture is being mobilized toward this depth, both from above and below, by physical properties of the tuff. The driving force for this movement of water may be evaporation aided by air flow within the fractures or along the surge beds found at the base of unit Qbt 2. Chloride and stable isotope analyses conducted by Newman (1996) support the presence of a dry region within the mesa resulting from deep evaporation.

Birdsell et al. (1999) discuss three distinct moisture content zones within the Bandelier Tuff beneath Area G and indicate that three different recharge rates are indicated by these moisture conditions. Within unit Qbt 2 and the upper portion of unit Qbt 1v, a recharge rate of zero to 0.1 mm/yr most closely matches site saturation data, whereas a range of about 0.1 to 1 mm/yr is needed to match moisture content data in the lower portion of the Tshirege Member. A recharge rate of about 10 mm/yr is required to match saturation data for the Cerro Toledo interval and the Otowi Member of the Bandelier Tuff. The vertical disconnects in these estimated recharge rates indicate that recharge is not steady state, or that significant moisture sources exist at depth (Newman et al, 2005). The elevated water contents in the Otowi Member in particular are likely remnant moisture from a wetter paleoclimate.

Groundwater

Within LANL, groundwater occurs in the deep regional aquifer and perched intermediate-depth and shallow aquifers. The regional aquifer occurs primarily within the Santa Fe Group, Puye Formation, and Cerros del Rio basalts at depths ranging from about 180 to 365 m (600 to 1,200 ft) bgs. The aquifer extends throughout the Española Basin (an area of roughly 6,000 km^2 [2,300 mi^2]) and reaches its maximum thickness of over 2,980 m (9,800 ft) beneath the Pajarito Plateau (Cordell, 1979). Beneath Area G, the regional water-table elevation is at approximately 1,737 m (5,700 ft) above msl (Stauffer et al., 2013), which is approximately 270 m (883 ft) bgs at well R-22 (LANL, 2002).

Groundwater flow in the regional aquifer beneath Area G is rapid. Stauffer et al. (2013, p. 39) use a velocity of 70 m/yr (230 ft/yr) for the path from beneath Area G to the PA compliance well (R-22).

Perched groundwater is generally detected only beneath relatively wet canyons (e.g., Los Alamos Canyon). Such occurrences are typically (1) shallow alluvial groundwater (generally at depths less than 30 m [100 ft]), or (2) deeper perched-intermediate groundwater that occurs in isolated zones separated from both alluvial and regional groundwater by unsaturated rock. Perched water forms mainly at horizons where properties of the medium change dramatically, such as at paleosol horizons containing clay or caliche. At TA-54, isolated perched-intermediate groundwater is observed at R-55 and R-23/23i, located 2500 and 2600 ft (0.75 and 1.1 km) east and southeast of MDA G, respectively, and in wells R-40/40i and R-37, both located approximately 5900 ft (1.8 km) northwest of MDA G. This water is thought to be localized beneath the canyon floors and to result from infiltration along Pajarito Canyon, which has a large drainage area. Perched-intermediate groundwater has not been observed beneath MDA G (LANL, 2011).

Annotated Bibliography of Area G Hydrologic Investigations

This section summarizes hydrologic-related studies and investigations conducted at or near Area G in which vadose-zone moisture content data were generated or considered, often in the context of larger investigation activities. The studies are presented in chronological order.

USGS, 1956

This memo from Clyde Conover of the USGS Water Branch in Albuquerque to Robert Dunning of the Atomic Energy Commission documents discussion of using Mesita Del Buey for waste disposal. The memo discusses general geologic features of the mesa, siting of pits away from natural drainages, and erosion potential. It also proposes leaving natural vegetation in place for erosion control.

Poland, 1960

This memo from J.F. Poland to John H. Abrahams, Jr. discusses an infiltration test in an infiltration pit on Mesita del Buey. It mentions moisture measurements in access tubes and water penetration to 7.6 m (25 ft) deep after 70 days. No other information is known about this infiltration pit such as its location.

Abrahams, 1963 (summarized by Rogers, 1977)

The USGS conducted an infiltration experiment in a small infiltration pit (1 m x 1 m x 1 m [3 ft x 3 ft x 3 ft]) located 3m (10 ft) south of Pit 2. A constant head of 23 cm (9 in) was maintained for 230 days during 1959 and 1960. The experiment was summarized in a draft report by Abrahams (1963), but a more complete summary is provided by Rogers (1977). Periodic measurements of water losses from the water supply tank were used to determine the water volume infiltrating the pit floor as a function of time. Moisture content was measured in 8 shallow boreholes located in the tuff surrounding the infiltration pit. In addition, photographs were taken of the wetting front that developed along the wall of Pit 2. Elevated moisture contents of up to 25 percent were observed to 6-7.6 m (20-25 ft) during the experiment.

Purtymun and Kennedy, 1971

This LANL document describes the basic geology and hydrology of Area G. Most of the information is accurate today with the exception of the thickness of Bandelier tuff which was found to be thinner than previously thought due to the large thickness of the Cerros del Rio basalt beneath Area G (LANL, 2005). This report also estimates erosion rates. They report an upper estimate of cliff retreat at 5E-4 to 8E-4 ft/yr (0.15 to 0.24 mm/yr). Appendix A of the report includes guidelines for constructions of pits at Area G.

Purtymun et al., 1978

Purtymun et al. (1978) describe five horizontal boreholes drilled under Pit 3 in 1976, and identified as P-3 MH-1 through P-3 MH5 and commonly known as “Medusa”. These boreholes were drilled from the eastern wall of Mesita del Buey. Core were collected to analyze for radionuclides and for joint orientation. The figures in the report showing borehole configurations are reproduced in McLin et al. (2005), and summarized below.

Rogers, 1979

This memo from Margaret Anne Rogers to James Steger documents neutron logging access tubes in Pits 1, 2, 7, 8, and 24. In addition, it documents that early access tubes were installed into pit floors. In one case, an access tube was installed to a depth of 35.7 m (117 ft) below the pit floor (in Pit 7).

Abeele et al., 1981

Abeele et al. (1981) provide a detailed discussion of the mechanisms and parameters relevant to the subsurface transport of radionuclides from LANL waste disposal areas through water migration and water vapor diffusion. The authors discuss the hydrology and hydrogeology of the Bandelier Tuff and summarize the results of hydraulic property testing (matric potential, saturation ratio, specific water capacity, water diffusivity, and hydraulic conductivity). They also briefly summarize the results of volumetric moisture monitoring conducted at Areas C, G, and F during 1978 and 1979.

Specific moisture content data for MDA G are not reported, but moisture monitoring in boreholes installed within fill material overlying MDA G pit 1 indicates that significant seasonal moisture content fluctuations occurred to a depth of approximately 4 m (13 ft) bgs. A downward moisture flux is indicated at greater depths. Moisture content data collected from boreholes installed in undisturbed tuff near MDA G shaft 50 indicate seasonal moisture content fluctuations in the upper 4 m (13 ft) of tuff, but show no significant changes at greater depths. Abeele et al. suggest that the presence of stable moisture "bulges" observed at depth in these boreholes result from variations in the moisture tension relationships of the tuff.

Kearl et al., 1986

In 1985 and 1986, a hydrological assessment of the vadose zone was performed at MDA G and MDA L in response to a New Mexico Environmental Department (NMED) compliance order (Kearl et al., 1986a). The study also evaluated the role of fractures in the transport of moisture through tuff. During the study, 23 boreholes were installed throughout TA-54, including 6 at MDA G, 15 at MDA L, and one in Zone 4. Core samples collected from the boreholes were evaluated for porosity, degree of welding, pumice content, hydraulic conductivity, and gravimetric moisture content. Permeability, water potential, and atmospheric pressure gradients were also evaluated in several boreholes. The MDA G and Zone 4 boreholes were installed to depths of approximately 37 m (120 ft) bgs.

Moisture contents were low overall with average values ranging from 2 to 4 percent by volume for the majority of the borehole moisture profiles. Higher values were generally observed within the top 3.1 m (10 ft) of the profile at MDA L and the top 4.6 m (15 ft) bgs of the profile at MDA G; two other zones of higher moisture were encountered within the lower portion of unit Qbt 1v-c and the top of unit Qbt 1g (depths ranging from approximately 31 to 38 m [100 to 125 ft] bgs). This zone is the vapor-phase notch described above. Volumetric water contents at these depths ranged from 11 to 28 percent in the MDA G boreholes and from 9 to 23 percent in the MDA L boreholes.

The water content and water potential data presented in this report likely represent relatively undisturbed conditions. Four of the MDA G boreholes were drilled in areas prior to pit excavations, and zone 4 is relatively undisturbed. The ambient volumetric water contents of 2 to 4 percent observed in undisturbed units Qbt 2 and Qbt 1v and reported in Kearl et al. (1986b) are described repeatedly in this report.

International Technology (IT) Corporation, 1987

The International Technology Corporation (IT Corp.) began vadose zone moisture monitoring in late 1985 at Areas G and L to analyze the infiltration and redistribution of meteoric water into the Bandelier Tuff in accordance with an NMED compliance order (IT Corp. 1987).

Two boreholes, one each in Areas G and L, were completed with aluminum casing for neutron-probe logging. The Area G borehole, LGN-85-08, was completed to about 15 m (50 ft) bgs and the Area L borehole, LLN-85-04, was completed to about 33 m (108 ft) bgs. Neutron probe moisture measurements were initiated on December 17, 1985 at the two areas. Measurements were collected approximately every two weeks through June 1986, after which data were not collected until early October 1986 (IT Corp., 1987, Appendix G).

Data were collected at depths ranging from about 0.6 to 30 m (2 to 98 ft). Volumetric moisture content remained essentially constant over time at depths below 4.6 m (15 ft) bgs. A consistent increase in volumetric water content of about 2 percent at all depths occurred between June and October 1985. Rather than being the result of infiltration, it is much more likely that this consistent increase is the result of a shift in the standard count measured with the neutron probe. For this reason, some researchers prefer to not use standard counts and count ratios (Kramer et al., 1995) for neutron probe measurements (refer to the neutron probe calibration section for more information).

Water content profiles for these two boreholes are shown in Figure 8. Borehole LLG-85-08 was drilled on the northwest edge of Area G. This is quite close to the location of samples collected from beneath the floor of Pit 38-Extension (described later), and data from those samples are included in Figure 8. Volumetric water contents from neutron logs of LGN-85-08 and from Pit 38-extension are very similar at about 2 percent, indicating undisturbed conditions below a depth of about 3 m (10 ft).

Purtymun, 1990

This report describes a proposed monitoring plan for Pit 37 for neutron logging and collecting liquid samples using a lysimeter system. It is notable that this system still exists in 2015 as polyvinyl chloride (PVC) and aluminum neutron access tubes in three locations in Pit 37 (west, central, and east). It also explains why some tubes are aluminum (for neutron logging) and some are 4-in PVC (for split-spoon sampling access).

Rogers and Gallaher, 1994

The Rogers and Gallaher Memo to Jake Turin dated December 19, 1994 presents moisture and in situ matric suction profiles for five boreholes installed in 1994. In addition, summaries of previously reported moisture data from Kearl et al. (1986a) and Krier et al. (1997) are provided.

Four boreholes, LGC-94-1, 2, 3, and 4, were drilled at MDA G to determine the extent of tritium migration near disposal shafts; and one borehole, LGC-94-5, was drilled to monitor for PCBs. Installation depths ranged from approximately 23 to 46 m (75 to 150 ft) bgs. Gravimetric moisture content data were obtained from both laboratory and radiological-van screening. Matric suction data were obtained using a chilled psychrometer methodology.

At boreholes LGC-94-1 through LGC-94-4, gravimetric moisture contents were found to be elevated (5 to 25 percent) in the upper 10 m (30 ft) bgs, low (1 to 2 percent) from 30 to 70 ft bgs, gradually increasing below depths of 80 ft bgs, with higher moisture contents above the Qbt 1v-c unit and at the VPN (Qbt

1v-c / Qbt 1g contact). Low gravimetric moisture was observed above and below the Qbt 2 / Qbt 1v-u contact. At borehole LGC-94-5 (also known as G-5, see Figure 9), water contents are higher than at the other four boreholes in the top 50 ft of the profile. This increase may be due to increased infiltration as a result of operational activities.

Rogers and Gallaher (1994) suggest that the elevated water contents in the upper 10 to 15 m (30 to 50 ft) of the profiles may be due to surface modifications such as road and buildings, and subsurface modifications such as pit and shaft construction.

1994-1995 RFI Investigation

As part of the TA-54 RFI for MDA G, 20 boreholes were drilled at MDA G during two drilling programs (LANL, 2000). In June 1994, two vertical boreholes designated as 54-01110 and 54-01111 were drilled in the southern portion of MDA G. Between September and December 1995, 18 additional vertical and angled boreholes were drilled. The locations of these 20 boreholes are shown in LANL (2000, Figure 3.3-8), and details of the boreholes are included in Table 1. Of these 20 RFI boreholes listed in Table 1, 12 have neutron logging data records and 7 remain open for potential future neutron logging. Some boreholes were converted to dedicated vapor monitoring boreholes. These RFI boreholes are also known as the 1100-series boreholes. The location of the 12 boreholes with neutron logging data, and G-5, are shown in Figure 9.

Profiles of volumetric water content for six boreholes, with Bandelier tuff stratigraphic contacts, are shown in Figure 10. Vold (1997c) has argued that the water content profiles of 54-01107 and 54-01121 appear to be affected by waste disposal operations. If true, borehole G-5 is also affected by operations while boreholes 54-01110 (below a depth of about 25 ft), 54-01111, and 54-01117 are not affected by waste operations due to their dryness in Qbt 2 and Qbt 1v zones. There are several reports summarized below that discuss the RFI borehole data further. In addition, some of the RFI boreholes have been used for routine moisture monitoring (discussed below).

Although not provided in the RFI report (LANL, 2000), boreholes 54-01110 and 54-01111 are probably 6-in diameter uncased boreholes, with surface casing only, and the other 18 RFI boreholes are 4- or 4.5-in diameter uncased boreholes, also with surface casing only. Newell's calibration data files indicate these are the borehole diameters. However, Jennings and French (2009) refer to these as 9-in and 5-in boreholes for the two sizes of RFI boreholes. Refer to the neutron probe calibration section below for more information.

Birdsell et al., 1995 and 1999

Birdsell et al. (1995) modeled the response of a steady-state saturation profile to a range of infiltration rates for an undisturbed, predisposal scenario and compared the results to measured, undisturbed borehole saturation values reported by Krier et al. (1997). Key findings from the study relevant to moisture content at Area G include the following:

- The modeled infiltration rates needed to fit the saturation values for upper Tshirege Member units Qbt 2 and Qbt 1v-u are lower than those needed to match moisture contents in the lower units.
- Normal yearly fluctuations in the infiltration rate are not a likely cause of the large difference in observed saturation values between the mesa top and deeper units. (To investigate the effect of a short-term [5-year] change in climate on subsurface saturation profiles, various wet-to-dry and

dry-to-wet combinations of infiltration rates were modeled. In each case, the short duration perturbation had no lasting effect on deep saturation values.)

- Evaporation along fractures and surge beds may explain the very low moisture levels seen in Tshirege Member units Qbt 2 and Qbt 1v-u and may further result in near-zero infiltration to the underlying units during the “normal drying state” put forth in the conceptual model. Simple assumptions of a fixed low saturation at the surge beds and a uniform infiltration rate predicted the saturation and capillary pressure profiles reported by Rogers and Gallaher (1995).

In a follow-up report in 1999, Birdsell et al. built upon the 1995 work and extended the model with the addition of hydrologic values obtained from within the Guaje Pumice Bed (Birdsell et al., 1999). These previously unpublished gravimetric moisture measurements from samples within the Guaje Pumice Bed ranged from 13.7 to 28.3 percent.

Loaiza and Vold, 1995

Loaiza and Vold (1995) describe the moisture measurements made in 11 boreholes drilled at Area G, and identified as 54G-NPH-1, 2, 3, 4, 5, 6, 7a, 7b, 7c, 8, and 9. The depths of the boreholes ranged from 9.8 to 35.4 m (32 to 116 ft) bgs. This report includes manufacturer neutron probe calibration coefficients for 2-in aluminum and 4- and 6-in PVC tubes that have been used since 1995 for the routine monitoring in access tubes located in waste pits. It should be noted that the “a” and “b” calibration coefficients in Table II are incorrect and reversed.

Water content profiles are included for boreholes in undisturbed tuff (unaffected by waste disposal activities and paving), where water contents are between 1-2 percent by volume in Unit 2 tuff below a depth of about 3.7 m (12 ft) bgs. Borehole 54G-NPH-2 is located close to the location of Pit 38-extension where samples were collected at a depth of 13.7 m (45 ft) and had an average water content of 1.9 percent by volume. One of the 11 boreholes is identified as 54G-NPH-5 and is located in about the same location as borehole G-5, and its profile is quite similar to the G-5 profile (Figure 10). Of the 11 boreholes, nearly all had the characteristics of undisturbed boreholes that have been previously described: a transient moisture shallow zone in the top 3-6 m (10-20 ft) bgs, followed by a dry zone with volumetric water contents of less than 5 percent extending to about 15 m (50 ft) deep. One borehole, 54G-NPH-1, appears to be one of the access tubes in Pit 37 (west) still in use. Another borehole, 54G-NPH-4, had high water contents ranging from about 16 to 30 percent throughout its 16.5 m (54 ft) profile. This borehole was clearly affected by disposal operations at Area G.

Loaiza and Vold (1995) also found that crushed tuff fill in active disposal units (e.g. Pit 37) has significantly higher water contents than undisturbed tuff which may be attributable to different hydraulic properties.

Turin, 1995

This report describes the conceptual model for subsurface transport beneath Area G. Turin describes a hydrologic system that is dominated by transient events, and conditions in the subsurface that are strongly influenced by the geometry of the mesa and the fractures in the tuff. Evaporation is identified as playing a major role in driving moisture movement. Turin also documents deep living roots observed at the bottom of Pit 38 at a depth of 18 m (60 ft), at the bottom of pit 39 at a depth of 13.7 m (45 ft), and as deep as 20.4 m (67 ft) at TA-33. Turin also describes a field experiment at TA-73 that measured rapid infiltration from snowmelt to depths of 15 to 30 m (50 to 100 ft), with water contents approaching saturation.

Turin is critical of the use of asphalt paving at Area G and refers to a “possibly misguided attempt to decrease infiltration.” However, the purpose of the asphalt paving at Area G was for support structures for buildings and for roads rather than for infiltration control.

Neeper and Gilkeson, 1996

Neeper and Gilkeson (1996) evaluated hydrogeologic data from select boreholes within TA-49 and MDAs G and L. Of particular interest were subsurface hydrogeologic conditions in boreholes with varying types of surface covers.

Gravimetric moisture content profiles were presented for two different boreholes at TA-49: one from an undisturbed area and the other from beneath an asphalt cover. The gravimetric moisture content profile beneath the asphalt cover was consistently higher than that of the undisturbed cover profile. Gravimetric moisture content profiles were presented for four different boreholes at MDA L: two from undisturbed areas, one beneath denuded ground, and one beneath an asphalt cover. Compared to the undisturbed profiles, the gravimetric moisture contents of the denuded area were elevated to a depth of 9.1 m (30 ft) bgs and those of the asphalt-covered area were elevated to a depth of 27 m (90 ft) bgs. Similar results were found in the two boreholes at MDA G (one beneath an asphalt cover [54-01102] and the other beneath a sparse grass cover [54-01106]). The asphalt-covered borehole had consistently elevated gravimetric moisture contents as compared to the sparse grass covered borehole. These results strongly indicate that the asphalt cover has inhibited moisture removal from atmospheric venting and vegetative transpiration.

In general, the VPN at the base of Qbt 1v-c is associated with a pronounced moisture peak at each of the widely separated boreholes. Matric suction was measured at MDA G and compared to gravimetric moisture content. A decrease in moisture content and a peak in matric suction were found at a depth near 18 m (60 ft) bgs. The result is an effective moisture barrier, marked by the movement of water downward from above and upward from deeper strata. This phenomenon is hypothesized to result from the movement of moisture out the sides of the mesa in response to barometric pumping.

Newman, 1996

Natural chloride and stable isotope tracers were used to examine the vadose zone hydrology beneath MDA G by Newman (1996). The study’s objectives included the quantification of vadose zone fluxes and pore water ages using chloride data and the examination of stable isotope (δ18O and δD) profiles for evidence of deep evaporation.

Chloride profiles were obtained from core sample pore water from four of the RFI boreholes (54-01107, 54-01117, 54-01121, and 54-01123); and pore water from one of the boreholes (54-01117) was analyzed for stable isotopes. Core samples collected from each borehole were evaluated for hydrogeologic parameters, including volumetric moisture content.

Volumetric moisture contents were variable with overall values ranging from 2 to 19 percent. Changes in chloride concentration generally corresponded with changes in volumetric moisture content, with high chloride concentrations occurring in zones of low moisture. High chloride concentrations and low volumetric moisture contents were found at the base of Qbt 2 in one borehole and within the Qbt 1v-u and 1v-c units in the other boreholes. Chloride concentrations at and below the VPN at the base of Qbt 1v-c were relatively dilute, corresponding with a substantial increase in volumetric moisture contents. Stable isotopes generally became lighter in both δ18O and δD with depth. However, stable isotopes were heavier than predicted beneath the theoretical 1.8-m (6 ft) zone thought to be influenced by surface evaporation.

Given the variability of the chloride and moisture profiles, flux data were presented in an attempt to normalize the chloride concentration to volumetric moisture content. Because flux is a measure of anion movement over time, it is indicative of moisture content in the vadose zone. For all boreholes, fluxes were highest near the surface (from 0 to 9.5 m [0 to 31 ft] bgs) and at depth (15.9 to 44.5 m [52 to 146 ft] bgs) and lowest at intermediate depths (9.5 to 15.9 m [31 to 52 ft] bgs). For intermediate depths, flux estimates were less than 1 mm/yr for all boreholes. For the upper and lower depths, fluxes were as high as 6 mm/yr (at 54-01117), and as low as 0.2 mm/yr at 54-01117.

In general, Newman found that the concurrence of high chloride concentrations, low volumetric moisture contents, small flux values, and relatively enriched stable isotopes in the mid-depths of the wells provides evidence of deep evaporation. Additionally, the large differences in chloride concentrations indicate substantial lateral variability in vertical flux and the amount of evaporation.

Puglisi and Vold, 1995

Puglisi and Vold (1996) evaluated the performance of Pit 37. This pit had been active for 5.5 years at the time of the study. For the evaluation, vadose zone characterization information was obtained from three horizontal boreholes installed beneath Pits 36, 37, originating from the floor of Pit 38. Core samples were submitted for a wide array of chemical and hydrogeologic analyses, including gravimetric moisture content.

The three boreholes were drilled in 1995 within Qbt 1v-u and 1v-c. The lengths of the boreholes ranged from about 46 to 83 m (151 to 267 ft) and depths ranged from approximately 11 to 14 m (35 to 45 ft) bgs. Seven core samples from each borehole were analyzed for gravimetric moisture content.

Volumetric water content data acquired from the boreholes indicate a gradual increase in water content with borehole distance. The increase in moisture content is likely due to the decrease in the elevation of the borehole, which causes it to enter the zone of elevated water contents associated with the vapor phase notch (McLin et al., 2005, Figure 4; Levitt, 2011, p. 4-8). It is unlikely that the increased water contents observed in the deepest 15-30 m (50-100 ft) of borehole H-2 are the result of infiltration due to the short period of time that the overlying Pit 36 disposal unit remained open (less than 1 year). Refer to the description of McLin et al. (2005) below for figures describing locations of these boreholes.

Rogers et al., 1996

Rogers et al. (1996) evaluated vadose zone infiltration rates beneath the Pajarito Plateau for mesa top and canyon bottom locations using vertical head gradients and empirically derived unsaturated hydraulic conductivity values. They found fluxes to be generally downward, although upward fluxes occur at some locations, and vapor flow appears to be a dominant factor in preventing downward liquid flux at MDA G. They hypothesize that evaporation due to air movement through the mesa contributes to low fluxes beneath MDA G. However, vertical downward fluxes in the upper 6 m (20 ft) of borehole G-5 are estimated to be 69 mm/yr (2.7 in/yr) indicating this location has been affected by disposal activities.

Krier et al., 1997

Krier et al. (1997) provided geologic, geohydrologic, and geochemical descriptions of stratigraphic units in the vicinity of Area G in support of the Area G PA and CA. The descriptions included data summarized from numerous published studies (Kearl et al., 1986b; Rogers et al., 1996) as well as previously unreported data for MDA G and L including hydraulic properties for all stratigraphic units down to the Santa Fe Group. Appendix B of Krier et al. (1997) provides a summary of moisture measurements taken from boreholes at MDAs L and G. Results are presented according to three types of borehole locations: (1) natural setting, (2) disturbed area, and (3) adjacent to disturbed area.

Seven boreholes located in the Zone 4 expansion area represented the natural terrain setting. Elevated gravimetric moisture contents were observed in the upper 4.6 m (15 ft) bgs, indicating the range over which precipitation influences subsurface moisture contents. Below 4.6 m (15 ft), variability in subsurface moisture contents was observed, indicating that deep atmospheric venting is affected by the heterogeneity of subsurface fracturing. All boreholes showed an increase in moisture content in the zone extending from the lower part of unit Qbt 1v-u to the VPN at the base of unit Qbt 1v-c. Beneath the VPN, moisture contents decreased in the upper portion of unit Qbt 1g.

Seven boreholes located at MDA L represented the disturbed area category. One borehole (location 54-01008) was installed within 6.1 m (20 ft) of a disposal shaft in barren, unvegetated ground not covered by asphalt. This borehole had elevated moisture contents in the upper 4.6 m (15 ft) bgs with much lower moisture contents below this depth (averaging <1 percent gravimetric). The low moisture contents at depth were attributed to the possible removal of moisture through barometric pumping. Another borehole (location 54-01009) was installed beneath an asphalt cover adjacent to disposal pits and shafts. As compared to the natural setting boreholes, the moisture contents in this borehole were elevated (from the ground surface to a depth of 27 m (90 ft) bgs). The elevated moisture profile for this borehole was attributed to the asphalt cover, which precluded ET and atmospheric venting. The remaining five boreholes were angled beneath inactive chemical disposal pits covered by asphalt and were constrained in depth to unit Qbt 2. The moisture contents of these angled boreholes were elevated in comparison to the moisture contents measured in boreholes located in natural settings, within the same stratigraphic unit. The elevated moisture contents were attributed to the asphalt covers, the liquid wastes disposed within the pits, and the role of the pits in transmitting precipitation to the subsurface.

Three boreholes located at MDA G represented the “adjacent to disturbed areas” category. Each borehole was installed near a waste disposal shaft. The moisture contents for these boreholes were variable. Two of the boreholes showed low moisture contents at the surge bed of the Qbt 2 / Qbt 1v-u contact. One borehole (location G-5) had gravimetric moisture contents above 4 percent at 1.5 to 15 m (5 to 50 ft) bgs but less than 1 percent in association with the surge beds at the base of unit Qbt 2.

Vold, 1997a (LA-UR-97-5184)

Vold (1997a) describes computational transport models with applications in three problem areas related to UZ moisture movement beneath Area G. The three areas include: 1) a 1-D transient analysis with average tuff hydraulic properties in the near surface region (in the top 3 m) with computed results compared to field data; 2) the influence on near surface transient moisture percolation due to realistic distributions in hydraulic properties derived statistically from the observed variance in the field data; and 3) the west to east moisture flow in a 2-D steady geometry approximation of the Pajarito Plateau.

Vold, 1997b (LA-UR-97-5185)

Vold (1997b) describes hydraulic property analyses on data collected from borehole G-5 and from new samples of the uppermost unit 2 tuff layer, as well as for surface soils. The data includes measurements of the unsaturated conductivity for samples from borehole G-5 using the Unsaturated Flow Apparatus. Vold reports the only known van Genuchten hydraulic property set for the VPN.

Vold, 1997c (LA-UR-97-5186)

Vold (1997c) describes calibrations of neutron probe counts to core samples collected in boreholes 54-01107, 54-01117, 54-01121, and G-5 using linear and power law fits, and using raw counts over a 16-second interval. Count ratios of neutron counts divided by standard counts are not used for these calibrations.

Based on the water content of these profiles, Vold suggests that boreholes 54-01121 and possibly 54-01107 are affected by waste disposal activities. Vold also suggests that borehole 54-01107 is centrally located at Area G and may represent conditions throughout a large region within Area G, as seen by the similarities in moisture profiles in several boreholes located near here including 54-01106 and G-5.

Vold, 1997d (LA-UR-97-5202)

Vold (1997d) describes the calculation of Darcy fluxes that are well matched to water content profiles from some of the RFI boreholes. The Darcy flux analyses indicate that moisture movement is significant (~cm/yr) and downward near the surface and small (~mm/yr) and upward in liquid and vapor phases through much of the lower portion of the Area G mesa. Vold estimates recharge rates of 0.5 to 1 cm/yr beneath active disposal units.

Bergfeld and Newman, 2001

Bergfeld and Newman (2001) analyzed core samples from MDA H boreholes 54-01023 and 54-15426 for anion, stable isotope, and gravimetric moisture profiles and compared these to results from MDA G. Borehole 54-01023 was drilled to about 80 m (260 ft) bgs during 1994 and 1995 RFI activities. In 2001, borehole 54-15426 was drilled near borehole 54-01023 to enable the collection of samples from greater depths (76 to 91 m [250 to 300 ft] bgs).

Forty-two samples of core leachate were analyzed for sulfate, chloride, fluoride, phosphate, bromide, and nitrate. Seven stable-isotope samples were analyzed for δ18O and δD. On-site gravimetric moisture measurements were made for some of the sampled intervals. When site-specific gravimetric moisture data were not available, values were interpolated from the measured intervals surrounding the sample.

Anion concentrations were inversely related to moisture contents along the profile: a broad zone across units Qbt 2 and Qbt 1v-u was characterized by elevated anion concentrations and conversely decreased moisture contents; near the Qbt 1v-c / Qbt 1g contact and extending to the base of the boreholes, anion concentrations decreased and moisture contents increased. Shallow samples (approximately 20 m [65 ft] bgs) were enriched with respect to δ18O and δD with a large deviation from the meteoric water line, indicating high evaporation rates. Deeper samples (from approximately 76 to 90 m [250 to 300 ft] bgs) were less enriched and plotted closer to the meteoric water line, indicative of lower evaporation rates.

Anion concentration profiles were used to quantify the downward flux, or transport, of anions. Results show that the low flux to high flux transition (low moisture to high moisture) occurs at the Tshirege Member unit Qbt 1v-c / Qbt 1g contact. Enrichment of stable isotopes supports the interpretation of the co-location of regions of low flux and increased anion concentrations to be the result of increased evaporation.

Newman et al., 2005

As part of the Area G PA maintenance program, two studies were conducted in 1999 and 2002 to better understand near-surface hydrologic conditions at Area G. The studies are summarized by Newman et al. (2005). The specific objectives of the studies were to (1) determine the appropriateness of using a uniform horizontal near-surface flux boundary condition for hydrological modeling of the groundwater pathway, (2) assess potential impacts of asphalt paving on site performance, and (3) evaluate potential effects of post-institutional control changes in site vegetation on near-surface hydrology. Both studies evaluated water content, pore water chloride, and stable isotope data from core samples collected from shallow boreholes (less than 2 m [6.6 ft] bgs) installed at numerous locations throughout MDA G and Zone 4.

During the 1999 study, near-surface hydrologic behavior was examined to compare similarities and identify differences between crushed tuff pit covers and adjacent areas that still retained part or all of the upper 1 to 2 m (3.3 to 6.6 ft) of in-situ soil or tuff. An additional objective of the 1999 study was to examine the hydrologic effects of asphalt paving at Area G. Water content, chloride concentrations, and stable isotope data from core samples collected in the unpaved areas were compared to core samples collected from three paved locations. Four additional core samples were collected from paved areas in 2002 to supplement the 1999 data.

During the 2002 study, the impact of plant succession on the near-surface hydrology of Area G was evaluated. Ten cores were collected in Zone 4 to evaluate how the transition of Area G from grassland to a piñon-juniper woodland following final closure of the facility would affect the near-surface hydrology of the site. Water content, pore water chloride, and stable isotope data collected from Zone 4 were compared to similar data collected from MDA G in 1999 and from three additional cores collected during 2002 from unpaved locations in MDA G.

No significant differences were indicated between pit covers and adjacent unpaved areas for the hydrologic variables evaluated. There was as much variation in moisture content values, chloride profiles, and stable isotope data within the pit covers and adjacent areas as there was between the two types of sites. Gravimetric moisture contents for pit covers ranged from approximately 2 to 14 percent, while moisture contents for unexcavated areas adjacent to the pits ranged from 2 to 24 percent. The 24 percent value was observed in a borehole (location 21b) near a paved area that received focused runoff. Excluding this borehole, the moisture contents for unexcavated areas adjacent to the pits ranged from 2 to 14 percent.

A comparison of the hydrological variables between paved and unpaved areas indicated that the estimated flux and water content values were higher for the paved areas than the unpaved areas. Stable isotope analyses also indicated that evaporation was minimal under the asphalt. Gravimetric moisture contents for paved areas ranged from 3 to 18 percent. Gravimetric moisture contents in unpaved areas within MDA G ranged from approximately zero to 19 percent. The 19 percent value was observed in a borehole (location G2) adjacent to a building suspected of having a leaking sump system. Excluding this borehole, the moisture contents for unpaved areas within MDA G ranged from approximately zero to 3 percent.

Gravimetric moisture contents in core samples collected from shallow boreholes in the Zone 4 piñon-juniper canopy ranged from approximately zero to 16 percent, and moisture contents in the Zone 4 intercanopy areas ranged from approximately zero to 9 percent. Stable isotope analyses indicated that more evaporation occurs in the intercanopy areas.

Vadose Zone Journal Special Issue 2005

In 2005, the Vadose Zone Journal published a special issue with papers specific to the geology and hydrogeology of LANL and the Pajarito Plateau. Twenty papers on LANL are part of this special issue. Most papers are not specific to Area G. However, two papers are described here for their relevance to vadose zone moisture at Area G: McLin et al. (2005) and Levitt et al. (2005).

McLin et al., 2005

McLin et al. (2005) describe horizontal boreholes drilled beneath waste disposal pits at LANL and used for moisture monitoring. Two sites are described: Site 1 is the drill pad for the five Medusa boreholes that extend beneath Pit 3 and previously described by Purtymun et al. (1978); and Site 2 is the drill pad formerly located at the bottom of Pit 38 for boreholes that extended beneath Pits 37 and 36 and previously described by Puglisi and Vold (1995). Plan and profile layouts for the Site 1 and Site 2 horizontal boreholes are shown in Figure 11 and Figure 12, respectively. McLin et al. (2005) provide data measured in 1992 from Site 1 by neutron logging four of the five Medusa boreholes, and from sampling pore water for tritium. For Site 2, they summarize the work of Puglisi and Vold (1995) and do not provide new data.

Volumetric water contents measured in the Medusa boreholes ranged from about 2-8 percent beneath Pit 3, and about 1-5 percent beneath the undisturbed mesa. Tritium concentrations were measured in pore water collected with absorbent collectors located along the length of P-3 MH-3, and measured tritium concentrations ranged from about 20 to 10,000 kBq/l (541K to 270M pCi/l).

Levitt et al., 2005

Levitt et al. (2005) present a comparison of the moisture profiles at MDA AB in TA-49 for two covers at the same site: as asphalt cover and an ET cover. Although this paper does not discuss Area G, its conclusions on the performance of asphalt covers are highly relevant to the temporary asphalt pavement covering much of Area G.

Levitt et al. (2005) found that water contents under the asphalt cover were near saturation, and decreased with depth but were elevated above ambient water contents to a depth of at least 20 m (66 ft) bgs. The asphalt cover at TA-49 was in place for 37 years before its removal, and cracks that developed in the asphalt cover were filled repeatedly over that time period.

Although the asphalt pavement covering large areas of Area G (particularly on the east end) is temporary and installed as a base layer for structures and not intended to be a hydrologic barrier, this layer is likely to be causing enhanced infiltration compared to undisturbed conditions, or waste pits covered with interim ET covers.

2005 MDA G Investigation Report

In 2005, investigation activities were conducted at MDA G to define the nature and extent of releases of hazardous waste constituents and/or radionuclides initially identified during the 1994-1995 Phase I RFI.

Also, additional information was collected on the hydrogeologic properties and other physical characteristics of the vadose zone beneath MDA G (LANL, 2005).

As part of the 2005 investigation activities, 36 vertical and 3 angled boreholes were drilled within MDA G to depths ranging from 21 to 170 m (68 to 556 ft) bgs. The locations of the 39 boreholes are shown in Figure 13. A summary of information on these boreholes is compiled in Table 2. The bottoms of most of these boreholes are located in the Otowi Member (unit Qbo) of the Bandelier Tuff to depths of approximately 61 m (200 ft) bgs. All but two of these 39 boreholes were drilled with hollow-stem auger methods.

Borehole 54-24523 (BH-15-2) was drilled to a total depth of 170 m (556 ft) bgs. Drilling problems due to loose sediments and basalt debris resulted in the need to drill borehole 54-25105 (BH-15-3), which is located 3 m (10 ft) to the north of BH-15-2. Note that BH-15-3 is identified as BH-15B in Figure 13, and that BH-15-2 is also known as BH-15A. These two boreholes were drilled with air-rotary, casing-advance methods. After drilling was completed, the casing was removed and 4-in, schedule-80 PVC was set in BH-15-3 to a depth of 508 ft bgs (LANL, 2005, p.7). The two boreholes appear to have been neutron logged before the original casing was removed, therefore there are no calibration data for the IR uncased boreholes.

Samples from these two boreholes were collected to assess geotechnical and hydrogeologic parameters, including saturated and unsaturated hydraulic conductivity, porosity, bulk density, moisture content, matric potential, and chloride anions. Profiles of measured gravimetric water content, water potential, and calculated volumetric water content, and saturation are shown in Figure 14.

Volumetric water contents in Units Qbt 2 and Qbt 1 are slightly elevated compared to profiles that represent undisturbed conditions at Area G. Water potentials in these units average about -3 bars which also suggests that this profile has experienced some wetting since disposal operations began in 1957. Undisturbed profiles usually have water contents of about 2 percent by volume, and water potentials drier (more negative) than -10 bars. Using the van Genuchten hydraulic properties for Qbt 2 reported in Levitt (2011), a water potential of about -50 bars corresponds to a volumetric water content of 2.5 percent.

All boreholes were neutron logged for in-situ volumetric moisture content. Measurements were taken at 4-cm depth increments throughout the profiles, and a five-point moving average was applied to smooth the profiles. Data from BH-15-1, -2, and -3 are shown in one plot. The 37 profiles are shown in Figure 15, Figure 16, Figure 17, and Figure 18. Note that these profiles are not identical to those reported in Jennings and French (2009) because an incorrect or unknown calibration equation to convert neutron counts into volumetric water content was used for the profiles in Jennings and French (2009). Refer to the neutron probe calibration section that follows.

Some boreholes appear to be relatively undisturbed, are located away from the effects of waste disposal operations, and have dry water content profiles typical of those discussed above for other undisturbed locations. Boreholes BH-22 (54-24382) and BH-23 (54-24383) are located north of Pit 2, and outside the fence line. These two boreholes have volumetric water content profiles of 2-3 percent down to the VPN, and dry again below the VPN, with slightly elevated water contents in the top meter or so.

Some boreholes are located in relatively undisturbed areas of Area G, and have quite dry profiles. Borehole BH-8 (54-24368) is an angled borehole located west of Pit 27, and is quite dry below a depth of about 3 m (10 ft). Borehole BH-37 (54-24397) is located at the southern edge of the mesa. Turin (1995) has suggested that there is increased air flow closer to the edges of mesas due to fracture networks. The dry profile in BH-37 may be due to the proximity of this borehole to the mesa edge and the increased vadose zone airflow.

However, boreholes located near mesa edges are not necessarily dry. Boreholes BH-16 (54-24376), BH-17 (54-24377), and BH-21 (54-24381) are all located near mesa edges and all three appear to have slightly elevated water contents to depths of about 15, 18, and 12 m (50, 60, and 40) ft, respectively. BH-32 (54-24392) is located near a mesa edge at the south end of Pit 17, but its profile appears to be affected by moisture to the VPN at a depth of about 23.5 m (77 ft) bgs.

Some boreholes appear quite dry and unaffected by disposal operations despite being located near disposal pits and roads. BH-13 (54-24373) is located near the south edge of Pit 37 and appears to be undisturbed below a depth of about 3 m (10 ft). Borehole BH-14 (54-24374) is located between trenches B and C and also appears to be undisturbed below a depth of 3 m.

There are some boreholes that appear to have been slightly affected by disposal operations with slight increases in water contents to depths of 15 m (50 ft) or less. These boreholes are located in relatively undisturbed areas that have vegetation and include BH-6 (54-24366), BH-7 (54-24367), BH-16 (54-24376), BH-29 (54-24389), and BH-33 (54-24393).

However, many of the 39 IR boreholes appear to be impacted by waste disposal operations from enhanced infiltration due to surface conditions, or from infiltration into nearby pits. Of all the 39 IR boreholes, only one, BH-35 (54-24395), appears to be wetted to greater than 50 percent saturation throughout most of its profile. This borehole is located at the east end of Pit 35, and sits between a structure with asphalt, and the main road through Area G. Interestingly, the upper 7.6 m (25 ft) of this profile dries with proximity to ground surface, suggesting that it experienced high infiltration years ago and has since been drying, or that it was wetted below a depth of 7.6 m by lateral flow.

Table 3 summarizes the moisture status of the 37 IR boreholes (excluding BH-15-2, 3) with respect to location and site characteristics, and includes the depth to which the borehole is undisturbed or apparently affected by waste disposal operations.

Area G Investigation Report Addendum (2007)

An Addendum to the 2005 IR (LANL, 2007) was completed in 2007, which describes additional drilling conducted to future determine nature and extent at all boreholes. The drilling included extending existing boreholes BH-2, BH-10, BH-26, and BH-34 to total depths at which the vertical extent of VOC contamination could be defined. An existing borehole (BH-37) near existing borehole 54-01111 was also extended to determine the vertical profile of tritium concentrations in the vapor phase at this location. Due to operational constraints at TA-54, borehole BH-2 could not be advanced, so a new borehole, BH-2b (54-27436) was constructed 2.6 m (8.5 ft) north of BH-2. Following drilling activities, these four boreholes were instrumented for vapor monitoring.

Sensor Installation at Pit 31 (2008)

During the closure of Pit 31 in the summer of 2008, 12 Campbell Scientific Inc. (CSI) CS610 time-domain reflectometry (TDR) probes were installed within the central portion of Pit 31 to record in situ volumetric water contents. The TDR probes were installed at 0.31 m (1 ft) intervals (two probes at each interval) beginning at 76 cm (2.5 ft) bgs with the deepest interval at the surface of the initial fill over the pit, approximately 2.3 m (7.5 ft) below the surface of the current pit waste cover. The TDR probe locations are shown in Figure 19. Data collection for this datalogger station began on 21 Aug 2008.

The 12 TDR probes are connected to a datalogger that collects daily data. The Topp equation (Topp et al., 1980) is used to convert raw data into volumetric water contents.

Sensor Installation at Pit 38-Extension (2012)

On July 12, 2012, 24 CSI heat dissipation probes (HDPs) were installed in the floor of the newly-excavated Pit 38-Extension (P38X) for the purpose of moisture monitoring beneath the pit floor in response to waste disposal activities. Enhanced infiltration may occur through the floors of open waste pits that have received water applications, usually as a result of dust suppression activities (Levitt, 2011). In addition, a greater portion of precipitation may infiltrate into pit floors because of lower ET. No plant transpiration occurs due to the lack of vegetation, and evaporation is reduced in deep (shaded) pits. HDPs were selected for this purpose because they are small and easy to install in a small borehole, and they have a large measurement range extending from hundreds of bars of suction to near-saturation. However, HDPs measure water potential rather than water content, so water content must be inferred from a water characteristic curve for backfilled crushed tuff.

During HDP installation, samples were collected from the bottom of each of three approximately 3 m (10 ft) deep boreholes, and analyzed for water content and water potential. Results of that sampling are summarized in Table 4. Gravimetric water contents for the four samples (including one duplicate sample) ranged from 1.0 to 1.5 percent, and water potentials ranged from -10.7 to -27.9 bars. The degree of dryness of these samples suggests that the sampled zone had not been affected by disposal operations.

After drilling, HDPs were installed and backfilled with crushed tuff that was generated during drilling each of the three boreholes. Figure 20 shows the approximate locations of the HDP boreholes in P38X. Figure 21 shows the sensor locations and depths in each of the three HDP boreholes. Data collection for this datalogger station began on 20 July 2012.

French et al., 2013

A Special Analysis (SA) was conducted to evaluate the impact from water applications to Pits 37 and 38 as a result of decontamination activities (French et al., 2013). Numerical modeling using HYDRUS-2D (Šimùnek et al., 2007) was conducted to simulate infiltration through the floors of Pits 37 and 38. Those results were then used to simulate flow through the UZ and the SZ with FEHM (Zyvoloski et al., 2007). The result of all calculations in the SA were that although calculated future dose was well below any regulatory limits, calculated breakthrough (at a hypothetical compliance water well) occurred in less than 1,000 years as a result of the decontamination water application.

Area G Moisture Monitoring

This section describes neutron moisture meter (i.e. neutron probe) moisture monitoring of boreholes located between and angled under waste disposal units, and of access tubes located within, under, and over waste disposal units. In addition, this section describes moisture monitoring conducted by automated datalogger systems for moisture probes located in a waste pit ET cover (Pit 31), and beneath a waste pit floor (P38X).

Neutron Probe Moisture Monitoring in Boreholes and Access Tubes

Moisture monitoring of Area G boreholes and access tubes has been conducted since the 1980s using neutron probes. However, many of those data records are now missing or difficult to locate. Some of these neutron logging data are well-documented. However, many older records include derived water content data, but the original neutron counts and standard counts are no longer available.

This section discusses moisture monitoring by neutron logging in boreholes and access tube in several subsections:

1) Medusa boreholes;
2) 1100-series RFI boreholes drilled in 1994-1995, and borehole G-5;
3) the IR boreholes drilled in 2005; and
4) access tubes located above, within, and below waste pits.

A map showing the locations of Medusa borehole P-3 MH-4, and access tubes above, within, and below waste pits is shown in Figure 22. A map showing access tubes in Pits 37 and 38 is shown in Figure 23.

Medusa Boreholes

The "Medusa Boreholes" are the five boreholes described above in Purtymun (1978) and McLin et al. (2005). Four of these five boreholes were neutron logged in 1992, and one of the five, P-3 MH-4, was logged 15 years later in 2007.

Raw neutron counts are not available for the 1992 dataset, but they are available for the 2007 dataset. Applying the calibration for a 4-in uncased borehole yields a profile that is drier than shown in McLin et al. (2005). Neutron counts were back-calculated from water contents for the McLin et al. (2005) profile for P-3 MH-4 using the incorrect calibration for 4-in open boreholes that was revealed during preparation of this report. Then those calculated counts were converted to water content using the correct calibration information and the profiles from 1992 and 2007 line up convincingly. Therefore, we conclude that the profiles presented in McLin et al. (2005) were calculated with an incorrect calibration.

The horizontal water content profiles with McLin et al. (2005) corrected data, and the profile measured in P-3 MH-4 in 2007 are shown in Figure 24. The reproducibility of the profiles in P-3 MH-4 is rather remarkable after 15 years. Some wetting has occurred on the hillslope to the east of Pit 3, and the profile under Pit 3 appears to have dried slightly at a borehole distance of 64-69 m (210-225 ft).

The dry water contents of these boreholes are notable. Volumetric water contents range between 1 to 3 percent for the 2007 log, which is consistent with undisturbed water contents for unit Qbt 2 described above. Some of the McLin et al. (2005) corrected water content data are below 1 percent by volume. This degree of dryness is not consistent with the profile from borehole BH-1 (25-24360) located close to the end of the profile for P-3 MH-4. BH-1 has a water content of about 10 percent at that depth, but BH-1 is likely impacted by enhanced infiltration due to asphalt. However, the dryness in the Medusa boreholes is consistent with water contents observed in borehole BH-21 (25-24381) located at the south end of Pit 3. BH-21 has a water content of about 1 percent at that depth (approx. 15 m [50 ft] bgs).

P3 MH-4 should continue to be logged as part of the Area G moisture monitoring program given its proximity to Pit 3, and its historical record. A Flute system (http://flut.com) has been used in the past for logging this borehole, but it could be logged using tremie pipe instead of a Flute system.

RFI Boreholes and G-5

Water content profiles for the 12 RFI (1100-series) boreholes with neutron logging records are shown in Figure 25 through Figure 28. The first set of these profiles are for the four 45-degree angled boreholes, 54-01105, 54-01106, 54-01114, and 54-01120 (Figure 25). These boreholes were logged in 1999 to 2001. This figure includes two y-axes for borehole length and depth bgs. This figure also includes the locations of the pit floor elevation relative to the borehole depth so that any influence of transient moisture while these pits were open can be evaluated. The slight increase in water content just below the pit floor seen in 54-01106, and above the pit floor in 54-01120 are not attributable to a stratigraphic unit change, and were reproduced in numerical model simulations described by Levitt (2011). Therefore, these slight increases are probably due to the influence of transient moisture while the pits were open.

Data from these profiles indicate that the top 3 m (10 ft) of boreholes 54-01105, 54-01106, and 54-01114 are likely affected by transient infiltration, but that the low water contents at depths of 3-12 m (10-40 ft) are indicative of undisturbed moisture conditions in Unit 2. Borehole 54-01120 has likely been influenced by enhanced infiltration to a depth of about 9 m (30 ft), probably from runoff from the north edge of Pit 2. The two profiles shown for 54-01120 do not line up as well as profiles in other boreholes, in part, because the 1999 logging was conducted every 0.6 m (2 ft) compared to the 2000 log which was conducted at every 0.3 m (1 ft) increment.

The second set of profiles is for RFI boreholes 54-01116, 54-01123, and 54-01125 (Figure 26). These boreholes were also logged between 1996 and 2001. The logs for 54-01116 and 54-01123 show very little change between 1996 and 2001, below the top 2 m. The 2009 log in 54-01125 clearly shows increased water contents in the Qbt 2 to a depth of about 12 m (40 ft) bgs. This borehole is located between Pits 3 and 5, and is covered by asphalt. As previously discussed, asphalt is known to cause enhanced infiltration. The 1996 log for this borehole was wetter than the 1999-2001 logs, suggesting that this borehole experienced some drying, followed by some wetting by 2009. All the logs for this borehole are very similar below a depth of 40 ft, at the Qbt 2/1v contact.

The third and fourth sets of profiles shown in Figure 27 and Figure 28 show profiles from RFI boreholes 54-01107, 54-01110, 54-01111, 54-01117, 54-0121, and G-5. These profiles also include the water contents measured from core collected during drilling of the boreholes. The good agreement between water contents from core and neutron logs provides confidence that the calibration used for the RFI boreholes is accurate (see section on neutron probe calibration).These two sets of boreholes were neutron logged many times between 1996 and 2001. The profiles at 54-01111 and 54-01117 show virtually no change in water content over the six-year period. Water content profiles in 54-01107 show some redistribution of moisture at depths of 18-21 m (60-70 ft) bgs, although water contents remain low (<5%). Water content profiles in 54-01110 show some changes in the top 3 m (10 ft) which is due to typical cycles of rain, snow, and ET, and show some redistribution at depths of about 11-14 m (35-45) ft bgs, but again at low water contents. Borehole G-5 also shows some redistribution with the profile showing some drying in the upper 15 m (50 ft) of the profile, and redistribution at depths of about 18-21 m (60-70 ft) bgs, similar to the behavior seen in 54-01107 and 54-01110. Profiles in borehole 54-01121 indicate significant wetting to a depth of 23 m (75 ft) between 1996 and 2001. This borehole is located in an area that accumulated runoff from surrounding asphalt. Runoff diversion structures have since been placed around this area to divert runoff.

2005 IR Boreholes

All of the 39 IR boreholes were neutron logged in 2005 after drilling was complete. Five of these boreholes have been logged since 2005: four in 2009; and one in 2013. The more recent, and original 2005 logs from these boreholes are shown in Figure 29 and Figure 30.

There is little change in water content in these five boreholes between the more recent and original logs. Some slight redistribution of moisture is apparent for the 4 boreholes in Figure 29. The profile shown in Figure 30 shows substantially more redistribution than the other 4 boreholes, with an apparent wetting front moving from about 12 m (40 ft) to about 21 m (70 ft) in a 4 year period. This borehole is located in the shaft field near borehole 54-01121 that has similar observed wetting due to runoff from surrounding asphalt. It is notable that the wetting in borehole BH-19 is not in the upper 12 m (40 ft) and is apparently due to lateral redistribution, near (and possibly the result of spreading at) the interface between Qbt 2 and Qbt 1v.

Water content data from samples collected beneath the floor of P38X are shown in Figure 29 for BH-13, because BH-13 is located near P38X. The water contents between the samples and the neutron logs are very similar. This provides an additional level of confidence that the calibration used for the IR boreholes is accurate (see section on neutron probe calibration).

The lower portions of the profiles measured in 2009 for BH-14, BH-16, and BH-19 are believed to be a result of borehole slumping that results in back-filling of the borehole. At depths of about 46 m (150 ft) bgs, it is difficult to feel a weight change when the neutron probe has reached the bottom of the borehole due to the weight of the cable. We suspect that these portions of these neutron logs occurred with the probe resting on the top of borehole slumped material. This suspicion can be confirmed by depth-tagging these boreholes the next time these boreholes are neutron logged.

Table 2 summarizes the status of all the IR boreholes. Rows that have grey shading indicate that these boreholes are no longer accessible for neutron logging.

Waste Disposal Pit Moisture Monitoring in Access Tubes

Moisture monitoring with neutron probes in access tubes within, under, or over waste pits has been conducted at Area G at least since 1996. However, Purtymun (1990) describes the proposed installation of access tubes in Pit 37 and the Rogers memo (1979) documents installation of access tubes in pit floors for moisture monitoring. Therefore, neutron probe moisture monitoring in access tubes at Area G may have begun as early as 1979. If so, any data records of such monitoring are likely missing.

In December 2006 and January 2007, a construction assessment and geodetic survey was performed for all of the neutron access ports except those located in Pit 15 (Jennings and French, 2009). Neutron ports located in Pit 15 were not evaluated due to active waste disposal operations. The assessment included camera logging to evaluate port condition and to determine whether there was clear access throughout the extent of each port. In total, 28 access ports were camera logged; 24 of these ports were determined to be clear. Table 5 summarizes the status of all neutron logging access tubes within, under, and over waste disposal pits at Area G. Rows that have grey shading indicate that these boreholes or access tubes are no longer accessible for neutron logging.

The following paragraphs describe the neutron log data collected at all waste disposal pit access tubes including those above Pits 6 and 7 (Dome 375 tubes), and in access tubes within waste zones in Pits 15, 30, 31, 37, 38, and 39.

Dome 375 has 3 sets of horizontal access tubes located under the dome and asphalt pad, but over waste disposal Pits 6 and 7. However, only the west and center tubes have a data record. The east tube has no data record and may be blocked. Horizontal profiles for these two tubes are shown in Figure 31. The 2006 profiles for both locations (green lines) are lower than the rest of the profiles and is likely the result of a high standard count for that day. In general, water contents have not varied much in the 10 year logging record. The highest water contents are measured in a gap between the two pits and beyond the footprint of the dome. This gap is covered by asphalt. As discussed previously, asphalt-covered areas may cause higher water contents and higher infiltration.

Pit 15 has six neutron logging access tubes. Four tubes are vertical and placed through the waste zone and into the pit floor and have been logged in 1999, 2000, and 2009. Two tubes are located at the north end of Pit 15 and are angled at about 45 deg at ground surface but curve into a horizontal orientation and are believed to extend along the length of the floor of Pit 15. These two angled/horizontal tubes have never been neutron logged. Note that the map in Figure 22 does not include the angled/horizontal tubes, and the map does not include the second tubes at Pit 15 Center and South locations.

Water content profiles measured in Pit 15 are shown in Figure 32. The tubes logged in 1999-2000 are identified only as C (center) and S (south), and it is not known if C is C1 or C2, and if S is S1 or S2, which are the tube identifiers from logging in 2009. The 1999-2000 logs are shallow, down to a depth of 6 m (20 ft) while the 2009 logs extend well below the pit floor, to a depth of about 12 m (40 ft) bgs. The higher water contents at the bottom of the profiles in 1999-2000 are not apparent in the 2009 logs, likely a result of redistribution following closure of Pit 15. The top of the neutron logs from 1999-2000 are at a depth of about 1 m (3 ft). This is an estimate for the location of the older logs given that Pit 15 was closed with an interim ET cover in 2008. The cover surface lies about 1 m (3 ft) above the surrounding ground surface.

Pit 30 has four, 4-in PVC, and two 2.5-in aluminum access tubes. Water content profiles measured in Pit 30 are shown in the bottom of Figure 32. The figures are identical except for the y-axis scale, where the right figure y-axis is 8 m (25 ft) in order to view the detail of the profiles measured in the PVC tubes.

The profiles measured in the aluminum tube (Al2) indicate some wetting from 1999 to 2006 and 2008 below a depth of 6.7 m (22 ft), and drying above that depth. The wetting trend below 6.7 m (22 ft) is notable and should be monitored again. Water contents remain quite low in this borehole, but it is not known if water contents have changed since the last log in 2008. The PVC tubes show little change between 2006 and 2008 for a given tube, however, there is some spatial variability in water contents shown between each of the PVC tubes (1, 2, 3, 4).

Pit 31 has one 4-in PVC access tube, and one 2.5-in aluminum access tube, both of which originally extended into the pit floor. Water content profiles measured in Pit 31 are shown in Figure 32. These tubes were logged in 2006, 2008, and 2009.

Water content profiles for the PVC and aluminum tubes were quite similar in 2006, and the profiles in the PVC tube have remained similar over the logging period, except above 3 m (10 ft) depth due to transient moisture cycles in 2008-2009. Logging data from the aluminum tube indicates some wetting to a depth of 7.6 m (25 ft), and elevated water contents above 3 m (10 ft) deep in 2008 and 2009. Data from the bottom 2 ft of the PVC tube indicate wet conditions during the 2008 log. This may be the result of condensation which has been observed in some access tubes.

Pit 31 was closed in 2008 with an interim ET cover. The cover surface lies about 1 m (3 ft) above the surrounding ground surface.

Pit 37 has 3 nests of access tubes located in the West, Center, and East portions of the pit (Figure 22). Some of these access tubes have been logged since 1996, and perhaps earlier than 1996 based on Purtymun (1990). Since 1996, the surface of Pit 37 has moved up in elevation as the pit received waste and was covered with layers of fill. As this progression occurred, PVC and aluminum extensions were added to the access tubes to increase their lengths. This is the case for all the access tubes in pits. Due to the intensive amount of logging that has occurred in Pit 37, it is challenging to reconstruct the elevation of the pit surface with time. Water content profiles measured in Pit 37 are shown in Figure 33. Plot (a) shows all data from 1996 through 2009, plot (b) shows data from 1996 to 2001, and plots (c) and (d) show data from 2006 to 2013 on two x-axis scales.

The records of pit elevation with time are not detailed, so this reconstruction was conducted using the best available information, and professional judgment. There are 3 previous ground surfaces shown in Figure 33 (a) and (b): at depths of 6.1, 5.5, and 3.4 m (20, 18, and 11 ft) bgs. The pit floor lies at a depth of about 19 m (62 ft) bgs.

Water content profiles measured in the aluminum tube (W_Al) show transient moisture cycles near the ground surface(s) but have an average water content of about 10 percent. Measurements were notably consistent between August 1996 and August 2001 at about 9 to 15 m (30 to 50 ft) bgs of the current pit surface.

The data from the PVC tubes in Pit 37 W1, W2, and W3 are remarkably similar, and indicate water contents of about 5 percent throughout the profile. These tubes were logged between 2006 and 2013. The bottom two measurements in tube W2 in 2013 indicate near-saturated conditions. As previously discussed, these water contents could be the result of condensation. They might also be the result of decontamination activities at Pit 37. The outfall from a truck wash station located on Pit 37 discharged at the south edge of Pit 38, and within about 15 m (50 ft) of the Pit 37 access tubes. It is feasible that the truck wash water infiltrated to the bottom of Pit 38 at a depth of 18 m (59 ft) and moved laterally to the bottom of Pit 37.

Water content profiles measured in the Pit 37 center tubes also required careful reconstruction, as the pit surface elevations differed from the Pit 37 west location. Profiles are shown in Figure 34 for the Pit 37 center tubes where plot (a) shows all data from 1996 through 2013, plot (b) shows data from 1997 to 2013, and plot (c) shows data from 2008 to 2013.

The profiles in the aluminum tube are very consistent in 1996-1997. The profiles in 1997 to 2000 are different from those in the previous year, and reach a shallower depth. Therefore, it is likely that these two sets of profiles were measured in two different aluminum tubes. The profiles shown for the PVC tubes are quite similar over the measurement period of 2008 to 2013, with average water contents of about 7 percent.

Water content profiles measured in Pit 37 east are also shown in Figure 34. There is one aluminum tube at the east location, with an accessible depth of about 6 m (20 ft) bgs. Profiles had a drying trend from 2006 to 2009, but show significant wetting in the 2013 log probably due to infiltration. This may be the result of dust suppression activities during the excavation of P38X, since the Pit 37 east tube is located near P38X.

Other than the measurements in tube W2 in 2013, there is no indication that the application of decontamination water to the cover of Pit 37 in 2011 (French et al., 2013) caused a change in water content profiles.

<u>Pit 38</u> has 12, 6-in schedule-80 PVC access tubes. Prior to 2013, none of these access tubes had been tagged (for depth) or neutron logged. In 2013, all but one tube was tagged, and six tubes were neutron logged. There is no documented neutron probe calibration for 6-in diameter, schedule-80 PVC for the Area G neutron probes, so a cross-calibration to 4-in schedule-40 PVC was developed (see next Section for details). Water content profiles measured in Pit 38 are shown in Figure 35. These profiles are quite consistent with volumetric water contents of about 10 percent using the developed calibration. Profiles are also shown in this Figure using a calibration for 6-in tubing from Loaiza and Vold (1995) (see next Section for details), and these profiles have an average volumetric water content of about 6 percent.

Decontamination water was applied to the western half of Pit 38 in 2012 (French et al., 2013), which includes areas with the W1 and S1 access tubes while the N1 tube is at the edge of the water application, and the NE tubes are located over 30 m (100 ft) east of the area of decontamination water application. However, the NE tubes (shown in heavy lines in Figure 35), are not drier than the other logs from Pit 38. In fact, the wettest measurement in Pit 38 was in a NE tube, located away from water application. Therefore, like the logs from Pit 37, the logs in Pit 38 do not show any evidence of water application conducted in 2011-2012 (French et al., 2013).

<u>Pit 39</u> formerly had three, 4-in PVC, and one 2.5-in aluminum (C) access tubes. After closure of this Pit in 2009, it now has only one (C2). Water content profiles from Pit 39 access tubes are shown in Figure 35. Profiles are quite consistent in the PVC tubes between 2006 and 2008. Tube C2 was logged after Pit closure in 2009, and therefore shows about 2.4 m (8 ft) of cover above the previous neutron logs. The 2009 profile shows that the profile has dried out slightly to a depth of about 7.6 m (25 ft) bgs. The profiles from the Al tubes (in red) are more erratic than the profiles in PVC tubes, with some wet spikes at a few depths. The Al tube also shows increasing water content with depth in 2008. The remaining PVC tube (C2) in Pit 39 should continue to be logged in the future to monitor the performance of this interim ET cover.

Pit 39 also has several access tubes that were installed on the pit floor before disposal began, and the tubes extend out of the ground at the NW edge of Pit 39. These tubes have never been logged, but they could potentially be camera logged and if they are still intact and not crushed, neutron logged.

The water content data presented above from access tubes in waste pits should be interpreted with caution. This is because waste pits contain waste in the form of many types of materials including steel, wood, plastics, and soil. Some pits are predominantly filled with bulk soil-like waste (e.g. Pit 37) while others are predominantly filled with steel boxes (e.g. Pit 38). A neutron probe measures a sphere of influence with a diameter of about 0.3-1 m (1-3 ft), depending on the water content, and therefore the probe may be strongly influenced by waste materials rather than measuring only the water content of the crushed tuff backfill. Possible air voids in the crushed tuff backfill due to bridging also contribute to the uncertainty in the neutron probe measurements in waste pits.

Neutron Probes and Calibrations

All neutron logging data collected since 1996 were measured with one of several 50-mCi Campbell Pacific Nuclear (CPN) Model 503DR Hydroprobes (also known as neutron probes). In some cases, the neutron probe used is identified in logging data, but in other cases, the particular neutron probe is unknown. All neutron logging data described in this report are based on 16-second (16s) count measurements.

Count Ratios

The use of count ratios is intended to eliminate effects caused by differences in probe responses by dividing out those differences. A standard count measurement is taken with the neutron probe placed in the lid of the probe carrying case. A count ratio equation usually takes the form of

$$VWC(\%) = \left(\frac{counts/16s}{16s\ standard\ count}\right) * A + B$$

where VWC is volumetric water content, and A and B are calibration coefficients that depend on the media being measured, and the borehole type (size, cased vs uncased, PVC vs aluminum, etc).

The neutron logging data measured in access tubes summarized in this report are based on calibrations with count ratios. But the neutron logging data measured in uncased boreholes are based on calibrations without count ratios in the form of

$$VWC(\%) = (counts/16s) * A + B,$$

or in the form of

$$VWC(\%) = A * \left(\frac{counts}{16s}\right)^B.$$

While the use of a count ratio is intended to normalize different probes, it can lead to problems if a standard count measurement is slightly high or low due to its use in the denominator of the calibration equation. For this reason, some researchers prefer to not use standard counts and count ratios. Kramer et al. (1995) report that random error in both the standard and measurement can compound, and that the shielded case used for the standard count can be subject to external influences. These influences could be wet versus dry soil beneath the shielded case.

Table 6 summarizes the three neutron probes known to have been used in Area G. In the logging data records, probe 00216 is frequently used, where 00216 is the Radioactive Sealed Source (RSS) Control number. Another probe is described as probe 848976 which is its barcode. This second probe has an RSS number of 00635. In this report, the probes are identified by RSS number only. Neutron logging conducted in 2013 was performed with probe RSS 00635.

Neutron Probe Calibrations

An important part of this report included a thorough investigation into the source and pedigree of neutron probe calibrations used in previous reports and papers such as Jennings and French (2009) and McLin et al. (2005). Investigations included analysis of original data files with measured water contents from core samples, and initial neutron logs. As a result of this research, we found errors in calibration equations, or calibration equations with no source/pedigree.

The original calibration datasets with water contents measured from core samples versus neutron counts for the RFI boreholes were found in the Dennis Newell file directory (see Appendix A). Regression analysis of these data are shown in Figure 36, and the calibration equations are summarized in Table 7. All neutron logging data in this report measured in boreholes were re-calculated using the verified calibration equations shown in Table 7.

As previously mentioned, the IR boreholes do not have calibration data because core was collected from BH-15-2 and BH-15-3, but the neutron logs were taken while the drill casing was in place. The IR boreholes are nominally 7 5/8 in (19.4 cm) diameter boreholes, so the 6-in (15.2 cm) calibration for the uncased RFI boreholes was used for the IR boreholes. The profiles for boreholes BH-15, BH-15-2, and BH-15-3 are shown in Figure 37. Also shown are volumetric water contents from core samples. The profile for BH-15-1 was calculated using the calibration for a 6-in uncased borehole. The profile for the BH-2, 3 profile (combined) was calculated using a site-specific calibration for core vs neutron counts in the casing-advance cased borehole.

The water content profiles for the IR boreholes presented in Jennings and French (2009) used the following incorrect calibration equation:

$$VWC(\%) = 8E5 * (counts/s)^{1.5366} * 100.$$

The correct equation is:

$$VWC(\%) = 7E5 * (counts/16s)^{1.5366}.$$

Neutron probe calibrations for 4-in PVC and 2.5-in aluminum access tubes are from Loaiza and Vold (1995, Table II), which are CPN factory calibrations. These access tubes are located in waste zones that are backfilled with crushed tuff, and in waste covers, also composed of crushed tuff. Although calibration data exist for neutron probe measurements in crushed tuff, conducted in drums (Nyhan et al., 1994), those calibrations were never used with the Area G data. Nyhan et al. (1994, Figure 25) report a count ratio calibration for crushed tuff in 2.5-in aluminum tubes that has a slope of about 25. The slope used in this report is about 17.5 (Table 7). The use of Nyhan's calibration would increase water contents by about a factor of 2. As shown in Figure 32 and Figure 34, profiles in aluminum tubes are higher than those in PVC tubes in Pit 31, and lower than those in Pit 30, and nearly the same as those in Pit 37C. This would suggest that the use of the factory calibration for 2.5-in aluminum is appropriate.

In the cover of Pit 31, there are neutron access tubes and TDR probes. A comparison of water contents measured by neutron probe and TDR for the same day is shown in Figure 38. The TDR measurements have higher water contents. The difference in these measurements could be due to the lack of a site-specific calibration for crushed tuff (e.g. Nyhan et al., 1994), or the use of the general Topp equation (Topp et al., 1990) for the TDR probes (rather than a site-specific calibration), or simply due to spatial variability of water content in the pit cover.

As part of future work to improve the moisture monitoring program at Area G, a new calibration could be conducted in crushed tuff using the Area G neutron probes. This could be conducted on a test plot with crushed tuff, or core samples could be taken from an interim waste cover adjacent to existing access tubes. In addition, a calibration of TDR probes in crushed tuff could be conducted in the laboratory. However, the waste disposal pits are a heterogeneous mixture of waste with crush tuff fill, and moisture monitoring will be most useful at understanding moisture trends than absolute moisture content values.

The calibration equation that has been used for 4-in PVC is from Loaiza and Vold (1995, Table II), and this calibration may actually be for class 125 PVC rather than for schedule-40 PVC (Reilly, 2013). Class 125 PVC has a thinner wall than schedule-40 PVC. If this equation is actually for class 125 PVC, then all water contents for 4-in PVC are underestimated.

In 2013, access tubes in Pit 38 were neutron logged for the first time. These access tubes are 6-in, schedule-80 PVC tubes, and there are no known calibration data for this size of tubing unless the 6-in PVC calibration in Loaiza and Vold (1995, Table II) is for schedule-80 tubing (schedule type not provided in this Table). A calibration equation for these tubes was calculated by assuming that they were measured in 4-in, schedule-40 PVC, and then making adjustments to 6-in, schedule-80 PVC based on the wall thickness and tubing diameter adjustments of Allen and Segura (1990). The net effect was that counts measured in the 6-in, schedule-80 PVC tubes were converted into water contents using calibrations for 4-in, schedule-40 PVC (from Loaiza and Vold, 1995), and then multiplied by a factor of 2.172. Using this correction factor results in a new calibration equation for 6-in, schedule-80 access tubes shown in Table 7. However, the calculated water contents using this method are generally higher than those in all other pits which is unlikely. Water content profiles for Pit 38 are shown in Figure 35 using both calibration equations (Loaiza and Vold, 1995, Table II, 6-in; and adjusted to schedule-80).

Pit 38 received large amounts of decontamination water in 2012, which might suggest that the interim cover logged in 2013 should be wetter than other covers, but Pit 37 also received decontamination water (in 2011), and its cover is not generally wetter than other interim covers.

Clearly, additional work could be done to resolve lingering questions about the neutron probe calibrations for Area G.

Figure 39 shows a comparison of all the neutron probe calibration equations used in boreholes and access tubes at Area G. In order to show calibrations with and without count ratios, calibrations that use count ratios were converted into 16s counts by dividing the 16s count by an assumed standard count of 6900, which is a typical value of a 16s standard count.

<u>Probe Comparison</u>

In 2009, two probes, RSS 00216 and RSS 00635 were compared. Following this probe comparison, one of the neutron probes (RSS 00635) was sent to CPN for servicing and refurbishment. A probe comparison was not conducted after servicing. Water content profiles were measured in the same borehole or access tube with the two probes within 1-2 days for two uncased boreholes, and 13 access tubes located in waste zones. The profile comparisons for two boreholes (54-24374 and 54-01125) and two access tubes (Pit 15 N1 and N2) are shown in Figure 40.

In the uncased borehole 54-24374 (BH-14), water contents appear nearly identical (Figure 40), although the average difference in percent volumetric water content throughout the profile was 0.62 with probe 00216 measuring slightly higher water contents. In the 5-in, uncased borehole 54-01125, average water contents were about 0.97 percent higher for probe 00216 compared to probe 00635. Note that calibrations for these two boreholes do not use standard counts (see Table 7).

Probe comparisons were also conducted in PVC and aluminum access tubes. Calibrations for the access tubes use a count ratio. In some cases, water contents were higher for probe 00635 than for 00216 as a result of a high standard count for probe 00216, which reduced the count ratio. Therefore, comparing counts instead of count ratios, probe 00635 counts are typically about 94 percent of probe 00216 counts.

This comparison reveals useful information on using multiple neutron probes at Area G. On one hand, the use of count ratios would help to normalize differences between different probes, but on the other hand, use of count ratios can cause problems if the standard count measurement is affected by external influences.

Cover Monitoring at Pit 31

A time series of daily measurements of volumetric water content measured with TDR probes in the interim ET cover over Pit 31 are shown in Figure 41.

After installation and completion of the interim ET waste cover at Pit 31, measured water contents ranged from about 17 to 21 percent. The influence of rain and snowmelt is not apparent in 2008-2009, which is likely due to the depths of the probes; the shallowest probe is 76 cm (2.5 ft) deep which may miss most cycles of rain and ET. However, starting in about March 2010, substantial wetting occurred throughout the ET cover, and this wetting is not associated with any rain or snowmelt. This increase is likely due to irrigation during a period in which a water truck was used to irrigate the newly-seeded waste cover. Following this period of likely heavy irrigation, the cover steadily dried out until the arrival of the 1,000-year storm in September 2013. Water contents had been decreasing after September 2013, but have been rising again since late 2014 possibly in response to snow melt.

As of April 2015, volumetric water contents in the Pit 31 cover range from about 13 to 19 percent or about 30 to 45 percent saturation. As vegetation becomes more established, the cover is expected to continue to dry out and mitigate net infiltration into the Pit 31 waste zone.

Pit Floor Moisture Monitoring in Pit 38-Extension

A time series of daily measurements of matric potential measured with HDPs beneath the floor of P38X are shown in Figure 42. The same data are shown with potential on a log scale in Figure 43.

Immediately after installation matric potentials decrease (become more negative) due to drying because the probes are installed with their ceramic porous cups saturated. The probes rapidly equilibrate to ambient conditions at matric potentials of -10 to -20 bars at the west borehole, and -25 to -50 bars at the center and east boreholes. The apparent seasonal response in 2012 and 2013 is an artifact of the effect of temperature on potential. During the winter of 2012-2013, infiltration causes the upper two sensors at the west and center boreholes to indicate wetted conditions which rapidly dry out.

As previously discussed, in September 2013, a 1,000-year storm delivered 17 cm (6.7 in) to Area G. At that time, P38X had been excavated but waste disposal had not begun. A photo, taken six days after the last day of the storm, shows ponded water in P38X (Figure 44). A plot showing the time lag for infiltration from the storm (and other precipitation) to reach each sensor is shown in Figure 45, where it is apparent that the shallower probes measured infiltration within days of the storm while the deeper sensors took more than a year to see the wetting front from the storm. Wetting also occurred at shallower depths immediately following the start of waste disposal in July 2014, probably due to dust control.

There are pros and cons to the timing of this storm, relative to sensor installation at P38X. One pro is that the storm provided a useful dataset of infiltration following the storm that can be used for future model calibration activities. One con is that the profile beneath P38X was wetted prematurely because the probes were intended to measure effects from waste disposal activities such as dust control and ambient precipitation while the pit is open.

As of February 2015, matric potentials are steady at about -1 bar for all sensors which corresponds to volumetric water content of about 10 percent, and a saturation of about 25 percent.

Summary

There is considerable evidence that the moisture content of the Qbt 2 caprock, and underlying Qbt 1v units are very dry under undisturbed conditions, unaffected by waste disposal operations. Under ambient, undisturbed conditions, seasonal cycles of rain, snow, snowmelt, ET and surface water runoff/run-on at Area G result in a transient moisture zone in the shallow surface soils, that can extend up to several meters into the caprock. Below this transient zone, units Qbt 2 and 1v have water contents of 2 to 3 percent before the characteristic increase at the VPN. Beneath the VPN, water contents return to low levels through unit Qbt 1g.

However, Area G has been an active waste disposal site for nearly 60 years, and many areas of Area G have been impacted by operations resulting in elevated water contents to depths of several meters, to several tens of meters. Many areas of Area G are covered with asphalt and structures, which have been demonstrated to cause enhanced infiltration and increased water contents. Once active disposal operations cease at Area G, the structures and asphalt are removed, permanent ET covers are installed, and the site is revegetated, elevated water contents are expected to eventually return to pre-1957 conditions (through drainage, airflow in fractures, and enhanced ET), with net infiltration returning to very small fluxes.

Although many of the boreholes drilled at Area G have elevated water content profiles, they are still relatively dry, with moisture contents at about 30 percent of saturation. Of all the borehole data presented in this report, one only IR borehole (BH-35, 54-24395) had moisture content greater than 50 percent of saturation throughout most of its profile, and this borehole is located at the east end of Pit 35 between structures, asphalt, and a road, and has no vegetation.

Moisture monitoring in access tubes in waste pits indicates that profiles are generally stable with no apparent increasing trends in water contents. There is some apparent redistribution of moisture in these tubes, but water contents are generally low, usually less than 10 percent by volume. Monitoring in access tubes and with probes in ET covers indicates that the interim ET covers are effective at mitigating net infiltration if vegetation is present.

Neutron logging offers the advantage of being highly repeatable, and precise, but questions remain related to the accuracy of the neutron probe measurements, particularly in access tubes. These questions can be resolved with some additional work. It is best to repeat measurements using the same probe, and to look for trends rather than absolute moisture content values.

Recommendations

As a result of research into all moisture monitoring data and studies related to Area G, we have recommendations for future work that would improve the defensibility of the moisture monitoring program.

Site-specific calibrations of neutron probe measurements in crushed tuff in waste covers (and waste pits) could be conducted by collecting samples with a bucket auger for moisture analysis in the laboratory, and comparing to neutron probe counts.

Site-specific calibrations of TDR measurements in crushed tuff could be conducted in the laboratory. Currently the Topp et al. (1980) equation is used to convert raw data into water contents, but a site-specific (crushed tuff) calibration is recommended.

While the use of standard counts and count ratios can lead to errors (previously discussed), they are useful for normalizing differences between probes, and to account for probe source decay with time. Therefore, we recommend the continued use of count ratios for the access tubes, in order to maintain continuity with previous data, but taking precautions described by Kramer et al. (1995).

Although many of the boreholes and access tubes described in this report should continue to be logged, there are several in particular that should be logged due to their historical record, for monitoring trends, and for ET cover performance monitoring. These boreholes and tubes include:

- P-3MH-4 (Medusa) located beneath Pit 3, due to its long historical record (since 1992)
- Several tubes in Pit 37, due to their long historical record (since 1996)
- Pit 30, Al-2, due to an apparent increasing trend in water content below the pit floor
- Borehole 54-01125, due to an apparent increasing trend in water content
- Borehole BH-19, due to an apparent increasing trend in water content
- Borehole BH-35, due to its high water content
- Pit 39, C2, because it is located in an interim ET cover installed in 2009
- Tubes in Pits 15 and 31 because they are located in interim ET covers installed in 2008

In addition, the horizontal access tubes that lie along the floors of Pits 15 and 39 should be logged (if accessible) as they would provide insight into moisture conditions at the bottoms of these pits.

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Tables

Table 1. Summary information of 1994-1995 RFI boreholes, and the G-5 and P3-MH4 boreholes.

Borehole ID	Other Names	Orientation, under Pit ID	Nominal Diameter	Depth (ft)	Borehole Casing	Surface Casing	Year Drilled	Year of Last log	Status
54-01102		32-deg; 32	4.5"	121.5' long, 86' deep	Open hole	Stickup	1995	Unknown	Unknown
54-01105		45-deg; 27	4.5"	68' long, 48' deep	Open hole	Stickup	1995	2001	
54-01106		45-deg; 25	4.5"	73.5' long, 52' deep	Open hole	Stickup	1995	2001	
54-01107		Vertical	4.5"	130	Open hole	Stickup	1995	2001	Dedicated VMB
54-01108		45-deg; 10	4.5"	73.5' long, 52' deep	Open hole	Stickup	1995	Unknown	Unknown
54-01110		Vertical	6"	102	Open hole	Stickup	June 1994	2001	Dedicated VMB
54-01111		Vertical	6"	153	Open hole	Stickup	June 1994	2001	Dedicated VMB
54-01112		Vertical	4.5"	60.5	Open hole	Unknown	1995	Unknown	Unknown
54-01113		Vertical	4.5"	17.5	Open hole	Flush	1995	Unknown	Abandoned
54-01114		45-deg; 17	4.5"	59' long, 42' deep	Open hole	Stickup	1995	2001	
54-01115		32-deg; 18	4.5"	135' long, 71.5' deep	Open hole	Stickup	1995	Unknown	Dedicated VMB
54-01116		Vertical	4.5"	89.5	Open hole	Stickup	1995	2001	
54-01117		Vertical	4.5"	90	Open hole	Stickup	1995	2001	Dedicated VMB
54-01120		45-deg; 2	4.5"	70' long, 49.5' deep	Open hole	Stickup	1995	2000	
54-01121		Vertical	4.5"	148	Open hole	Stickup	1995	2001	Dedicated VMB
54-01123		Vertical	4.5"	100	Open hole	Stickup	1995	2001	
54-01124		30-deg; 4	4.5"	77' long, 38.5' deep	Open hole	Unknown	1995	Unknown	Unknown
54-01125		Vertical	4.5"	63.5	Open hole	Stickup	1995	2009	
54-01126		30-deg; 3	4.5"	102' long, 51' deep	Open hole	Stickup	1995	Never	Dedicated VMB
54-01128		30-deg; 1	4.5"	82.5' long, 41' deep	Open hole	Stickup	1995	Never	Dedicated VMB
54-G-5	LGC-94-5	Vertical	6"	94	Open hole	Stickup	1994	2001	FLUTe setup
P3-MH-1	Medusa MH1	Horiz.; 3	4"		Open hole	Stickup	1976	Unknown	Cap rusted closed
P3-MH-2	Medusa MH2	Horiz.; 3	4"	288' long	Open hole	Stickup	1976	1992	
P3-MH-3	Medusa MH3	Horiz.; 3	4"	273' long	Open hole	Stickup	1976	1992	
P3-MH-4	Medusa MH4	Horiz.; 3	4"	304' long	Open hole	Stickup	1976	2007	
P3-MH-5	Medusa MH5	Horiz.; 3	4"	241' long	Open hole	Stickup	1976	1992	
Shading indicates not available for neutron logging									
VMB = Vapor monitoring borehole									

Table 2. Summary information of 2005 Investigation Report boreholes.

Borehole ID	Other Names	Orientation, under Pit ID	Nominal Diameter	Depth (ft)	Borehole Casing	Surface Casing	Year Drilled	Year of Last log	Status
54-24360	BH-1	Vertical	7 5/8"	200	Open hole	14', flush	2005	2005	
54-24361	BH-2	Vertical	7 5/8"	170	Open hole	10-20', flush	2005	2005	
54-27436	BH-2B	Vertical	7 5/8"	192	Open hole	10-20', flush	2007	Never	Dedicated VMB
54-24362	BH-3	Vertical	7 5/8"	189	Open hole	10-20', stickup	2005	2005	
54-24363	BH-4	45-deg; 8,9,10	7 5/8"	250' long, 177' deep	Open hole	10-20', stickup	2005	2005	
54-24364	BH-5	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2005	
54-24366	BH-6	45-deg; 20,18	7 5/8"	250' long, 177' deep	Open hole	10-20', stickup	2005	2005	
54-24367	BH-7	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2005	
54-24368	BH-8	45-deg; 26,25	7 5/8"	250' long, 177' deep	Open hole	10-20', stickup	2005	2009	
54-24369	BH-9	Vertical	7 5/8"	250	Open hole	10-20', ??	2005	2005	Not found in 2012
54-24370	BH-10	Vertical	7 5/8"	225	Open hole	10-20', flush	2005/2007	2005	Dedicated VMB
54-24371	BH-11	Vertical	7 5/8"	200	Open hole	10-20'	2005	2005	Not found (snow)
54-24372	BH-12	Vertical	7 5/8"	250	Open hole	10-20'	2005	2005	Covered with fill
54-24373	BH-13	Vertical	7 5/8"	250	Open hole	10-20', stickup	2005	2013	
54-24374	BH-14	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2009	
54-24375	BH-15	Vertical	7 5/8"	201	Open hole	10-20', flush	2005	2005	
54-24523	BH-15-2	Vertical	7 5/8"	556	6" PVC?	10-20', flush	2005	2005	Not found in 2012
54-25105	BH-15-3	Vertical	7 5/8"	701	4" PVC Sch-80 casing to 508'	10-20', flush	2005	2005	
54-24376	BH-16	Vertical	7 5/8"	200	Open hole	10-20', stickup	2005	2009	
54-24377	BH-17	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2005	
54-24378	BH-18	Vertical	7 5/8"	183	Open hole	10-20', flush	2005	2005	
54-24379	BH-19	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2009	
54-24380	BH-20	Vertical	7 5/8"	196	Open hole	10-20', flush	2005	2005	
54-24381	BH-21	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2005	
54-24382	BH-22	Vertical	7 5/8"	147	Open hole	10-20', stickup	2005	2005	
54-24383	BH-23	Vertical	7 5/8"	148	Open hole	10-20', stickup	2005	2005	
54-24384	BH-24	Vertical	7 5/8"	68	Open hole	10-20', stickup	2005	2005	CDB borehole
54-24385	BH-25	Vertical	7 5/8"	177	Open hole	10-20', flush	2005	2005	
54-24386	BH-26	Vertical	7 5/8"	186	Open hole	10-20', flush	2005/2007	2005	Dedicated VMB
54-24387	BH-27	Vertical	7 5/8"	81	Open hole	10-20', stickup	2005	2005	CDB borehole
54-24388	BH-28	Vertical	7 5/8"	181	Open hole	10-20', flush	2005	2005	
54-24389	BH-29	Vertical	7 5/8"	200	Open hole	10-20', stickup	2005	2005	
54-24390	BH-30	Vertical	7 5/8"	186	Open hole	10-20', flush	2005	2005	
54-24391	BH-31	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2005	
54-24392	BH-32	Vertical	7 5/8"	200	Open hole	10-20', stickup	2005	2005	
54-24393	BH-33	Vertical	7 5/8"	206	Open hole	10-20', flush	2005	2005	
54-24394	BH-34	Vertical	7 5/8"	200	Open hole	10-20', stickup	2005/2007	2005	Dedicated VMB
54-24395	BH-35	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2005	
54-24396	BH-36	Vertical	7 5/8"	200	Open hole	10-20', flush	2005	2005	
54-24397	BH-37	Vertical	7 5/8"	200	Open hole	10-20', flush	2005/2007	2005	Dedicated VMB
Shading indicates not available for neutron logging									
VMB = Vapor monitoring borehole									
CDB = Canada del Buey									

Table 3. Summary of moisture status and site description of Investigation Report boreholes.

Borehole	Borehole ID	Location	Moisture Status	Borehole Site Description
BH-1	54-24360	Between Pits 1-3	Ambient below ~100 ft	Between buildings, asphalt
BH-2	54-24361	N of Pit 6	Ambient below ~90 ft	In a dirt road, no vegetation
BH-3	54-24362	Between Pits 7 and 24	Ambient below ~60 ft	Possibly wetted by irrigation, drainage from asphalt
BH-4	54-24363	E of Pit 8	Bulge at 45 ft	Relatively undisturbed area, some vegetation
BH-5	54-24364	S of Pit 12	Ambient below ~50 ft	In a dirt road, no vegetation
BH-6	54-24366	E of trenches A-D	Ambient below ~25 ft	Relatively undisturbed area, some vegetation
BH-7	54-24367	Between Pits 21-22	Ambient below ~50 ft	Relatively undisturbed area, some vegetation
BH-8	54-24368	W of Pit 27	Ambient below ~10 ft	Away from disposal activities
BH-9	54-24369	Between Pits 27-28	Ambient below ~70 ft	Actively used area, no vegetation
BH-10	54-24370	Between Pits 29-30	Ambient below VPN	Actively used area, no vegetation, next to busy road
BH-11	54-24371	Between Pits 32-33	Ambient below VPN	Shaded by building, snow shadow, asphalt
BH-12	54-24372	Between Pits 35-36	Ambient below ~60 ft	Unknown, covered by fill pile
BH-13	54-24373	SW of Pit 37	Ambient below ~10 ft	Relatively undisturbed area, some vegetation
BH-14	54-24374	Between Trenches B-C	Ambient below ~10 ft	Relatively undisturbed area, some vegetation
BH-15	54-24375	Between Pits 12-13	Ambient below ~60 ft	In a dirt road, no vegetation
BH-16	54-24376	NW of trenches A-D	Ambient below ~50 ft	Relatively undisturbed area, some vegetation; near mesa edge
BH-17	54-24377	N of Trench A	Ambient below ~60 ft	Edge of dirt road, some vegetation; near mesa edge
BH-18	54-24378	NE shaft field	Ambient below ~75 ft	Disturbed area, little vegetation
BH-19	54-24379	Near 33 shafts	Ambient below ~50 ft	In paved road, asphalt, former sump area
BH-20	54-24380	E of Pit 19	Ambient below ~60 ft	Disturbed area, little vegetation
BH-21	54-24381	S of Pit 3	Ambient below ~40 ft	Relatively undisturbed area, some vegetation; near mesa edge
BH-22	54-24382	N of Pit 2	Ambient below ~5 ft	Outside fence, ambient conditions
BH-23	54-24383	N of Pit 2	Ambient below ~5 ft	Outside fence, ambient conditions
BH-24	54-24384	Canada del Buey	Dry in Qbt 1g	Canada del Buey canyon borehole
BH-25	54-24385	Between Pits 2-4	Ambient below ~40 ft	Between buildings, asphalt
BH-26	54-24386	Between Pits 4-5	Ambient below VPN	Between buildings, asphalt
BH-27	54-24387	Canada del Buey	Wetting in Qbt 1g	Canada del Buey canyon borehole
BH-28	54-24388	N of Pit 6	Ambient below VPN	In a dirt road, no vegetation
BH-29	54-24389	Next to G-5	Ambient below ~50 ft	Relatively undisturbed area, some vegetation
BH-30	54-24390	Between Pits 10-12	Ambient below VPN	Disturbed area, little vegetation
BH-31	54-24391	S of Pit 16	Ambient below ~70 ft	Relatively undisturbed area, some vegetation
BH-32	54-24392	S of Pit 17	Wetted to VPN	Relatively undisturbed area, some vegetation; near mesa edge
BH-33	54-24393	E of Pit 30	Ambient below ~45 ft	Disturbed area, little vegetation
BH-34	54-24394	E of Pit 33	Ambient below VPN	Disturbed area, little vegetation
BH-35	54-24395	E of Pit 35	Wetted to TD; drying in upper 25 ft	High water contents; Disturbed area, little vegetation, downslope of asphalt surface
BH-36	54-24396	N of trenches A-D	Ambient below ~55 ft	Trench area
BH-37	54-24397	S of trenches A-D	Ambient below ~10 ft	Near mesa edge

Table 4. Laboratory Measurements of Water Content and Potential from Borehole Cuttings.

Sample Number	Loc ID	Location	Grav. water content (%)	Water potential (-bars)	Average Grav. water content (%)	Average Water potential (-bars)
MD54-12-17947	54-1	East	1	27.9	1	27.9
MD54-12-17951	54-2	Center	1.5	24.8	1.35	25.9
MD54-12-17955	54-3	West	1.4	10.7	1.4	10.7
MD54-12-17963 (duplicate)	54-2	Center	1.2	26.9		

Table 5. Summary information of neutron logging access tubes in, under, and over waste pits.

Borehole or Tube ID	Other Names	Orientation	Nominal Diameter	Depth (ft)	Borehole Casing	Year of Last log	Status
54-27727	Dome375_W	Horiz; over Pit 6	4"	144' long	PVC, Sch-40	2008	Open
54-27728	Dome375_C	Horiz; over Pit 6	4"	138' long	PVC, Sch-40	2008	Open
54-27729	Dome375_E	Horiz; over Pit 6	4"				Unknown
54-27733	Pit15_NE	Ang./Horiz.	6"	Unknown	PVC, Sch-40		Unknown
54-27734	Pit15_NW	Ang./Horiz.	6"	Unknown	PVC, Sch-40		Unknown
	Pit15_C1	Vertical	4"	40	PVC, Sch-40	2009	
	Pit15_C2	Vertical	4"	40	PVC, Sch-40	2009	
	Pit15_S1	Vertical	4"	41	PVC, Sch-40	2009	
	Pit15_S2	Vertical	4"	15	PVC, Sch-40	2009	Blocked at 15'
54-27717	Pit30_1	Vertical	4"	25	PVC, Sch-40	2009	Blocked at 15'
54-27718	Pit30_2	Vertical	4"	23	PVC, Sch-40	2009	
54-27719	Pit30_3	Vertical	4"	20	PVC, Sch-40	2009	
54-27720	Pit30_4	Vertical	4"	25	PVC, Sch-40	2009	
54-27721	Pit30_Al1	Vertical	2.5"	6	Aluminum	2009	Blocked at 6'
54-27722	Pit30_Al2	Vertical	2.5"	65	Aluminum	2009	
54-27745	Pit31	Vertical	4"	42	PVC, Sch-40	2009	
54-27746	Pit31_Al	Vertical	2.5"	47	Aluminum	2009	
54-27735	Pit37W_1(w)	Vertical	4"	56	PVC, Sch-40	2013	
54-27736	Pit37W_2(c)	Vertical	4"	61.5	PVC, Sch-40	2013	
54-27737	Pit37W_3(e)	Vertical	4"	59	PVC, Sch-40	2009	
54-27738	Pit37W_Al	Vertical	2.5"	9	Aluminum	2001	Blocked at 9'
54-27739	Pit37C_1	Vertical	4"	39.5	PVC, Sch-40	2013	
54-27740	Pit37C_2	Vertical	4"	37.5	PVC, Sch-40	2013	
54-27741	Pit37C_Al	Vertical	2.5"	6	Aluminum	2001	Blocked at 6'
	Pit37E1(w)	Vertical	4"	5	PVC, Sch-40		Blocked at 5'
	Pit37E2(e)	Vertical	4"	2	PVC, Sch-40		Blocked at 2'
	Pit37E_Al	Vertical	2.5"	18	Aluminum	2013	
	Pit38W1(n)	Vertical	6"	59	PVC, Sch-80	2013	
	Pit38W2(c)	Vertical	6"	28	PVC, Sch-80		Tagged in 2013
	Pit38W3(sw)	Vertical	6"	7	PVC, Sch-80		Tagged in 2013
	Pit38W4(s)	Vertical	6"	58	PVC, Sch-80		Tagged in 2013
	Pit38W5(se)	Vertical	6"	27	PVC, Sch-80		Tagged in 2013
	Pit38S1	Vertical	6"	>70	PVC, Sch-80	2013	
	Pit38S2	Vertical	6"	Unknown	PVC, Sch-80		Unknown
	Pit38N1(w)	Vertical	6"	47	PVC, Sch-80	2013	
	Pit38N2(c)	Vertical	6"	39	PVC, Sch-80		Tagged in 2013
	Pit38NE1(w)	Vertical	6"	12	PVC, Sch-80	2013	
	Pit38NE2(c)	Vertical	6"	14	PVC, Sch-80	2013	
	Pit38NE1(e)	Vertical	6"	11	PVC, Sch-80	2013	
54-27742	Pit39C2	Vertical	4"	46	PVC, Sch-40	2009	
54-27723	Pit39_gateW	Ang.+Horiz.	6"	9	PVC, Sch-40		Turns horiz. at 9'
54-27724	Pit39_gateE	Ang.+Horiz.	6"	6	PVC, Sch-40		Obstruction at 9'
54-27725	Pit39_NW1	Ang.+Horiz.	6"	Unknown	PVC, Sch-40		Turns horiz. at 85'
54-27726	Pit39_NW2	Ang.+Horiz.	6"	Unknown	PVC, Sch-40		Turns horiz. at 42'
Shading indicates tubes not available for neutron logging							

Table 6. Neutron probes used in Area G.

RP3 Source Control #[1]	LANL barcode	S/N	Probe Date	Last use	Notes
00635	848976	H310700379	3/13/1991	2013	Compared to RSS 00216 in 2009
00216	?	D73115093	?	2009	In 2013, probe had display problems, wouldn't recharge, loose RCA plug
000676	?	H36076933	?	?	

[1]Also known as Radioactive Sealed Source (RSS) #

Table 7. Summary of neutron probe calibrations.

Borehole Type	Construction	Diameter	Calibration Equation	Calibration Information	Source
7 5/8 " IR boreholes	Open hole (uncased), 10' surface casing	7 5/8 in	vwc%=7E-5*16s_cnts^1.5366	Core vs counts for borehole BH-15-2,3; data close to Newell calibration	Newell calibration filename "6inchholes.xls"
6-inch RFI boreholes, and G-5	Open hole (uncased), 10' surface casing	6 in	vwc%=7E-5*16s_cnts^1.5366	Core vs counts for boreholes 54-01110, 54-01111, and 54-G-5	Newell calibration filename "6inchholes.xls"
4.5-inch RFI boreholes	Open hole (uncased), 10' surface casing	4.5 - 5 in	vwc%=2E-4*16s_cnts^1.3404	Core vs counts for boreholes 54-01107, 54-01117, and 54-01121	Newell calibration filename "4.5inchholes.xls"
4-inch Medusa boreholes	Open hole (uncased), 10' surface casing	4 in	vwc%=2E-4*16s_cnts^1.3404	Core vs counts for boreholes 54-01107, 54-01117, and 54-01121	Newell calibration filename "4.5inchholes.xls"
Waste pit access tube	2-in Aluminum casing	2 - 2.5 in	vwc%=cnt/std_cnt*17.4556-1.2378	Manufacturer Calibration	Loaiza and Vold, 1995, Table II (A & B switched)
Waste pit access tube	4-in, sch-40 (?), PVC casing	4 in	vwc%=cnt/std_cnt*29.0912-1.2361	Manufacturer Calibration	Loaiza and Vold, 1995, Table II (A & B switched)
Waste pit access tube	6-in, sch-40 (or 80?), PVC casing	6 in	vwc%=cnt/std_cnt*29.0912-1.2361	Manufacturer Calibration	Loaiza and Vold, 1995, Table II (A & B switched)
Waste pit access tube	6-in, sch-80, PVC casing	6 in	vwc%=cnt/std_cnt*63.1861-2.6848	Use Loaiza and Vold calibration for 4-in, sch-40 tubes, then multiply by 2.1722	Adjustment factors from Allen and Segura, 1990

Figures

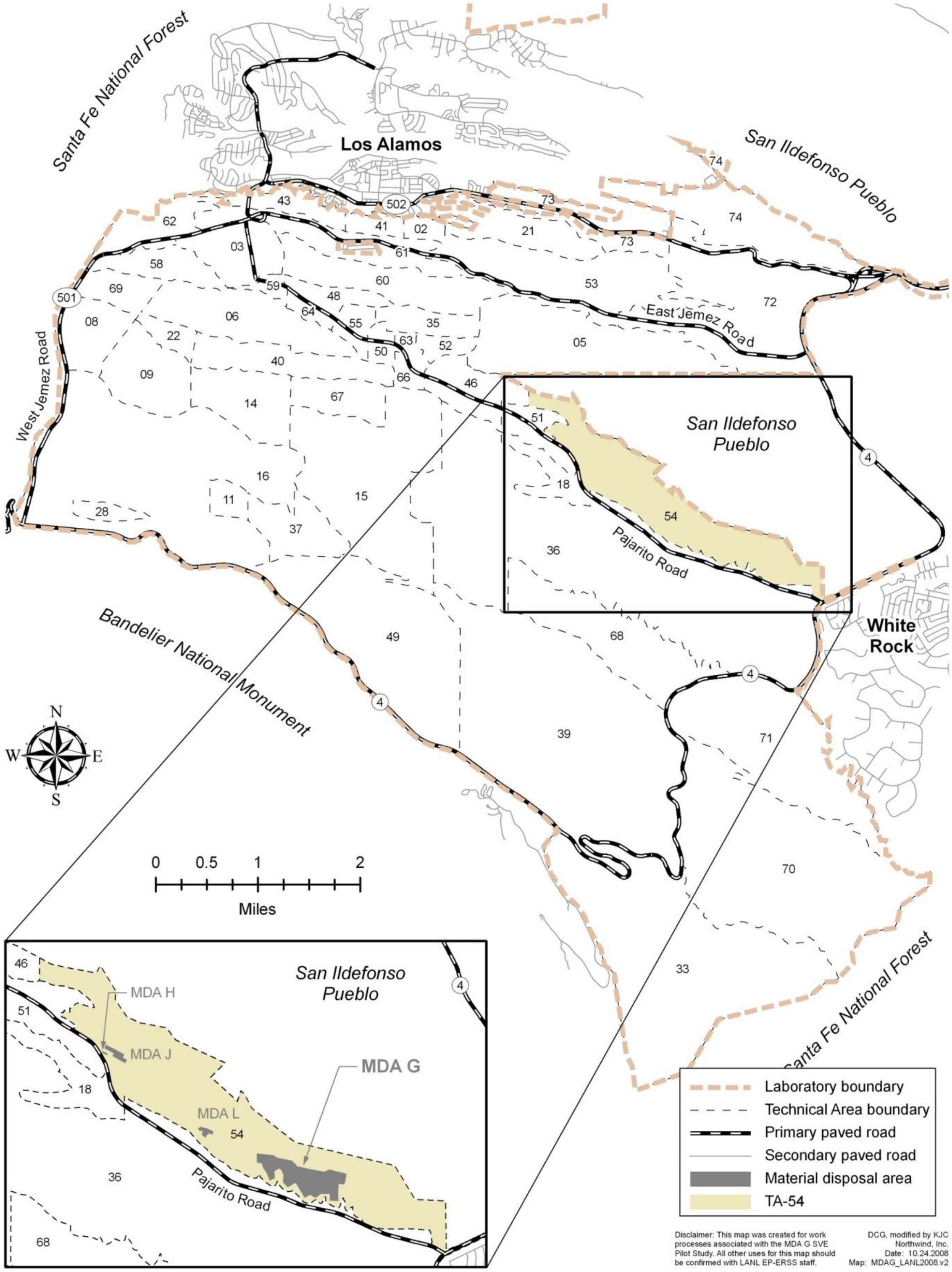


Figure 1. Location of MDA G within LANL.

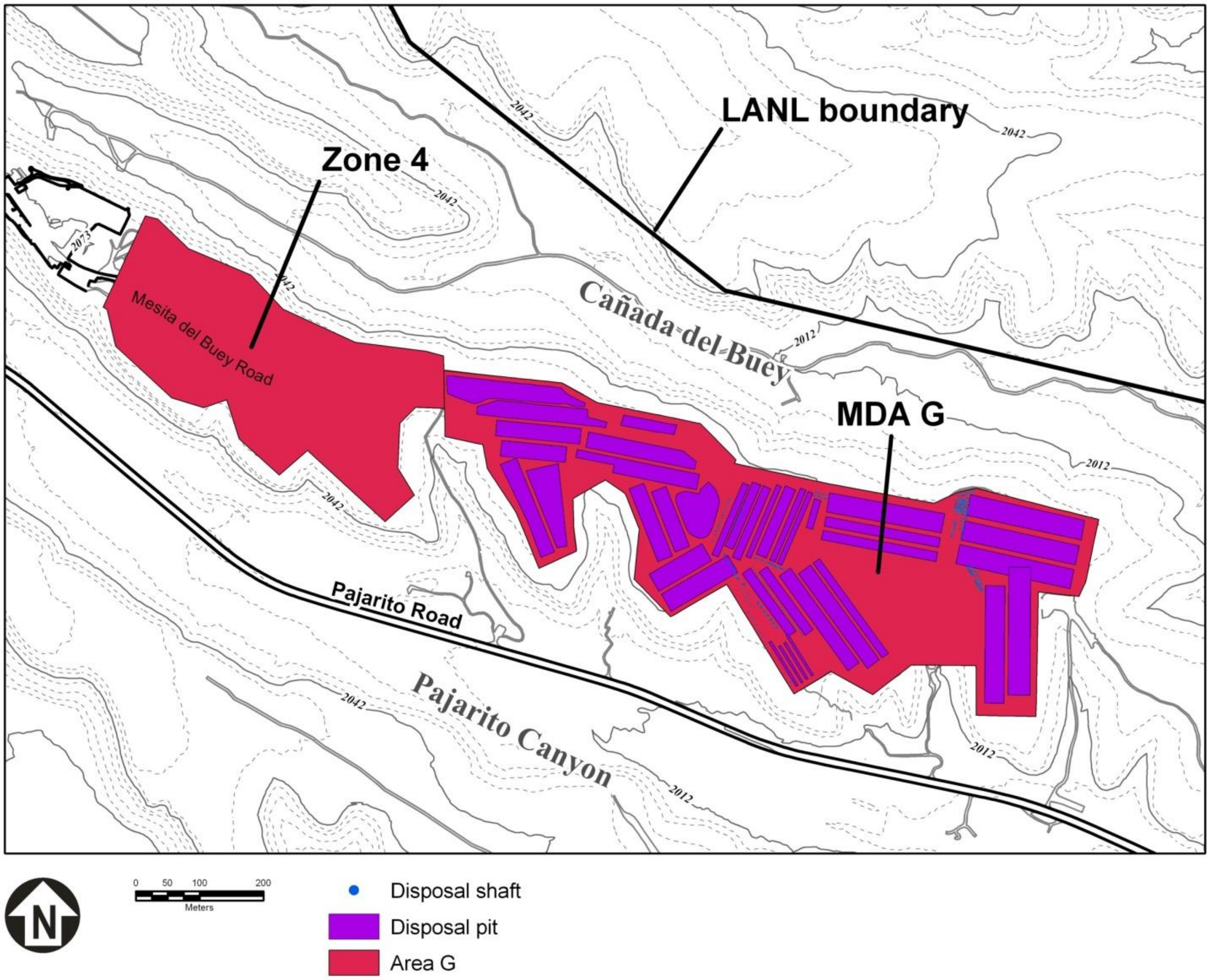


Figure 2. Locations of MDA G and the Zone 4 expansion area.

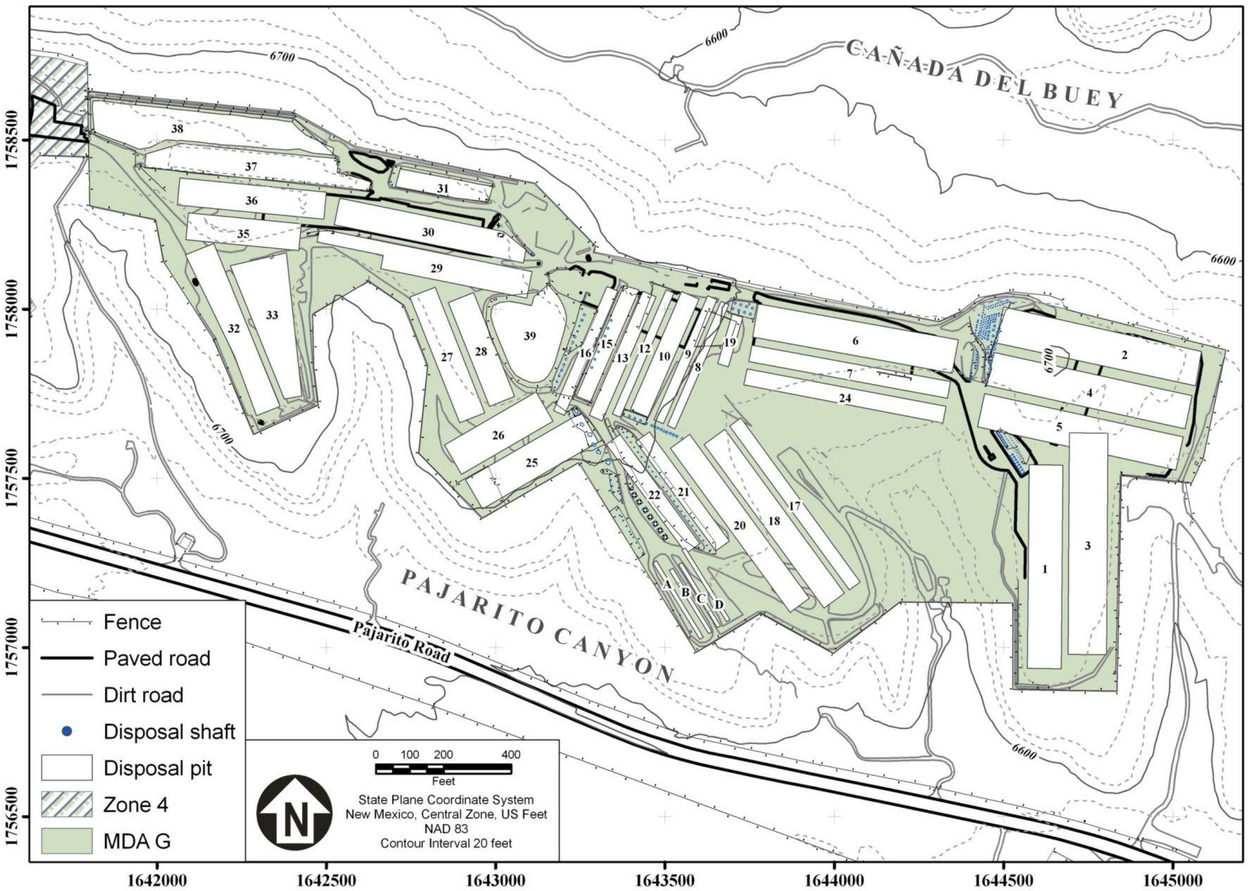


Figure 3. Waste disposal units at MDA G.

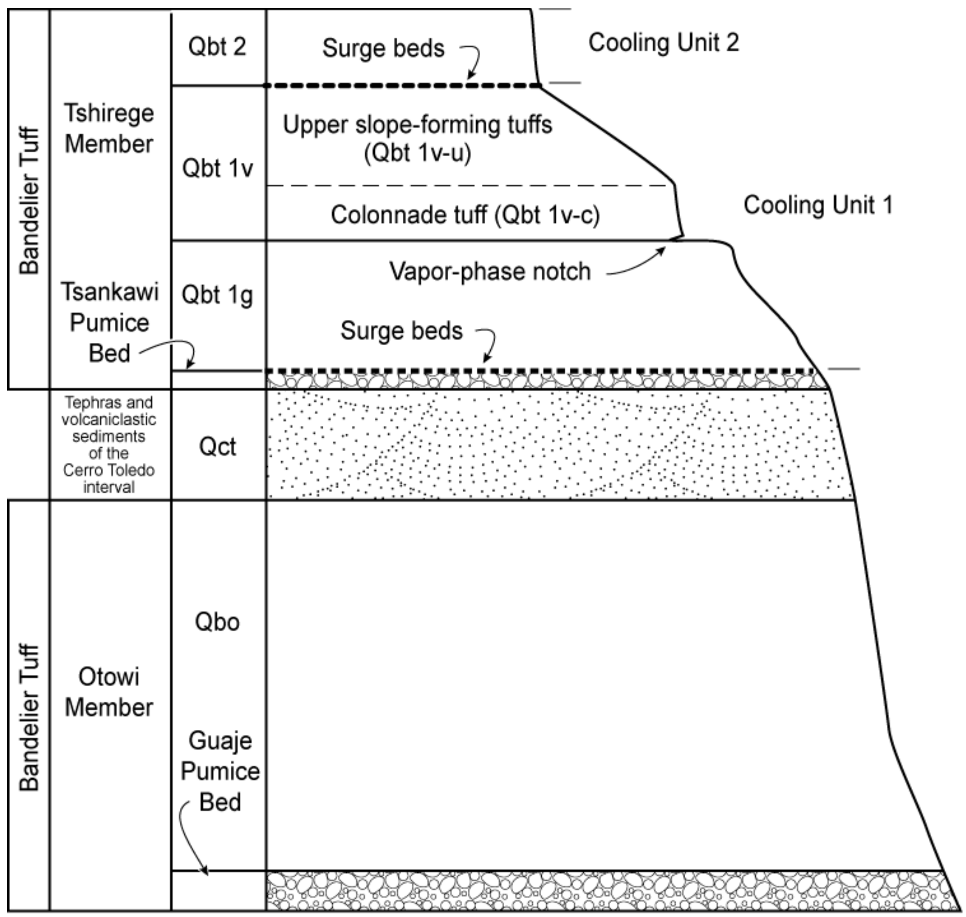


Figure 4. Generalized stratigraphy of the Bandelier Tuff beneath Area G (Adapted from Broxton and Reneau, 1995).

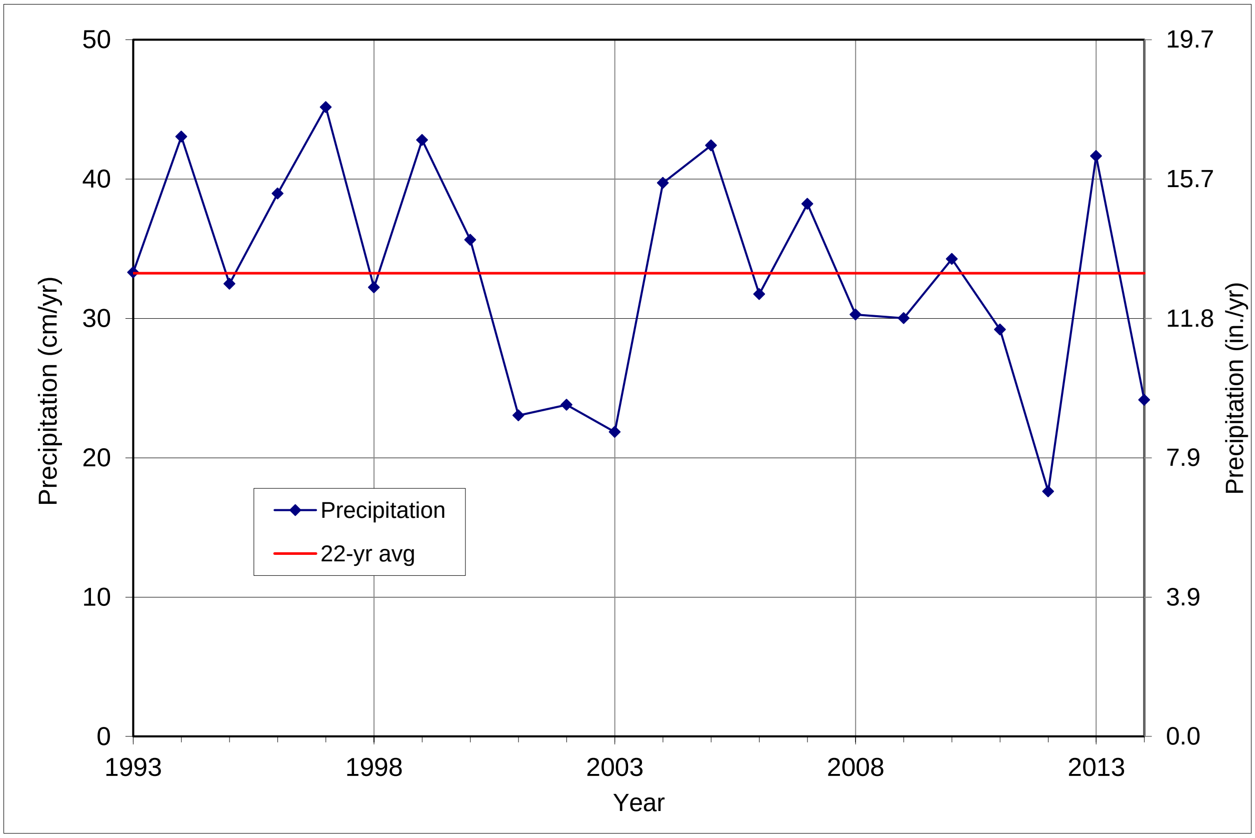


Figure 5. Annual precipitation measured at TA-54 meteorology station from 1993-2014.

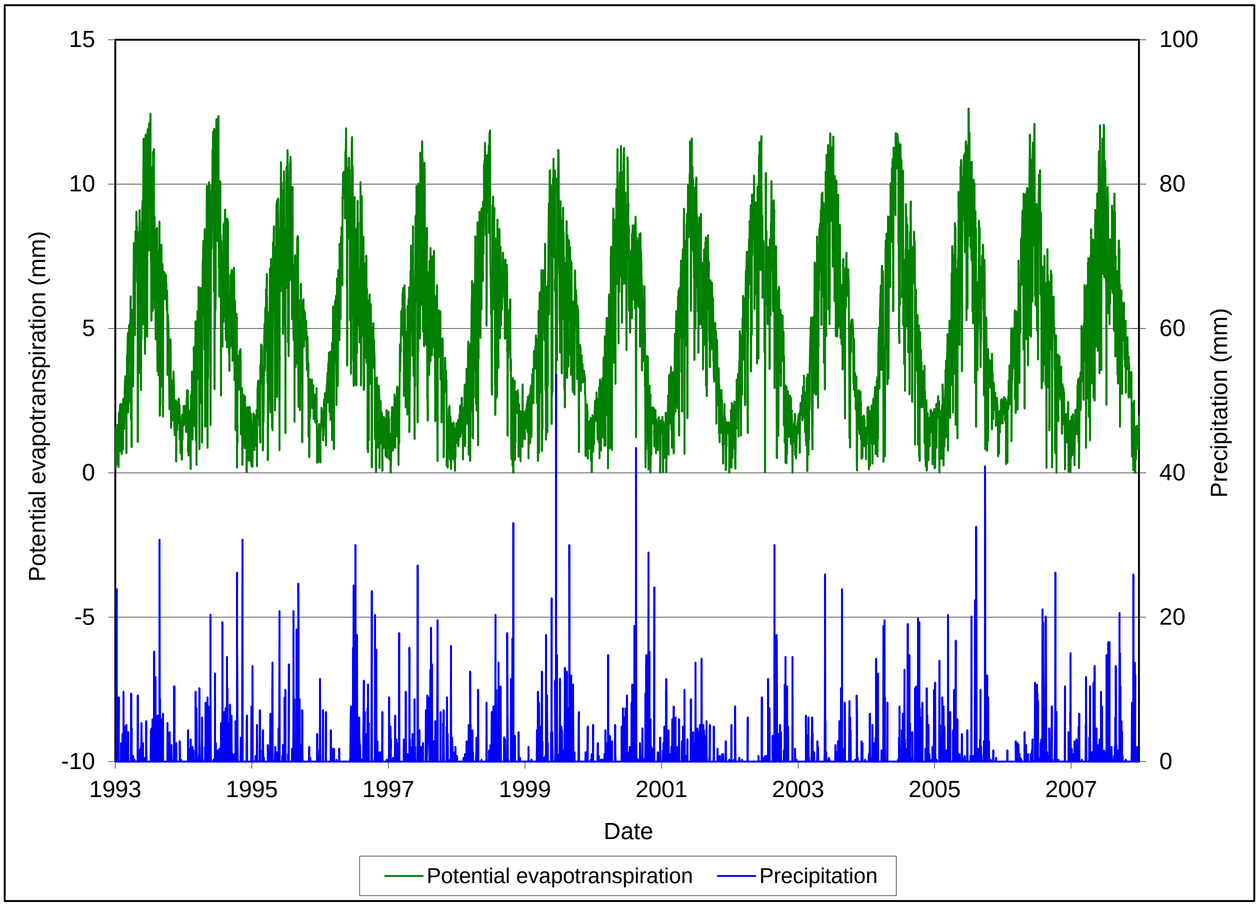


Figure 6. Potential evapotranspiration calculated with TA-54 meteorology data (from Levitt, 2008, Figure 2).

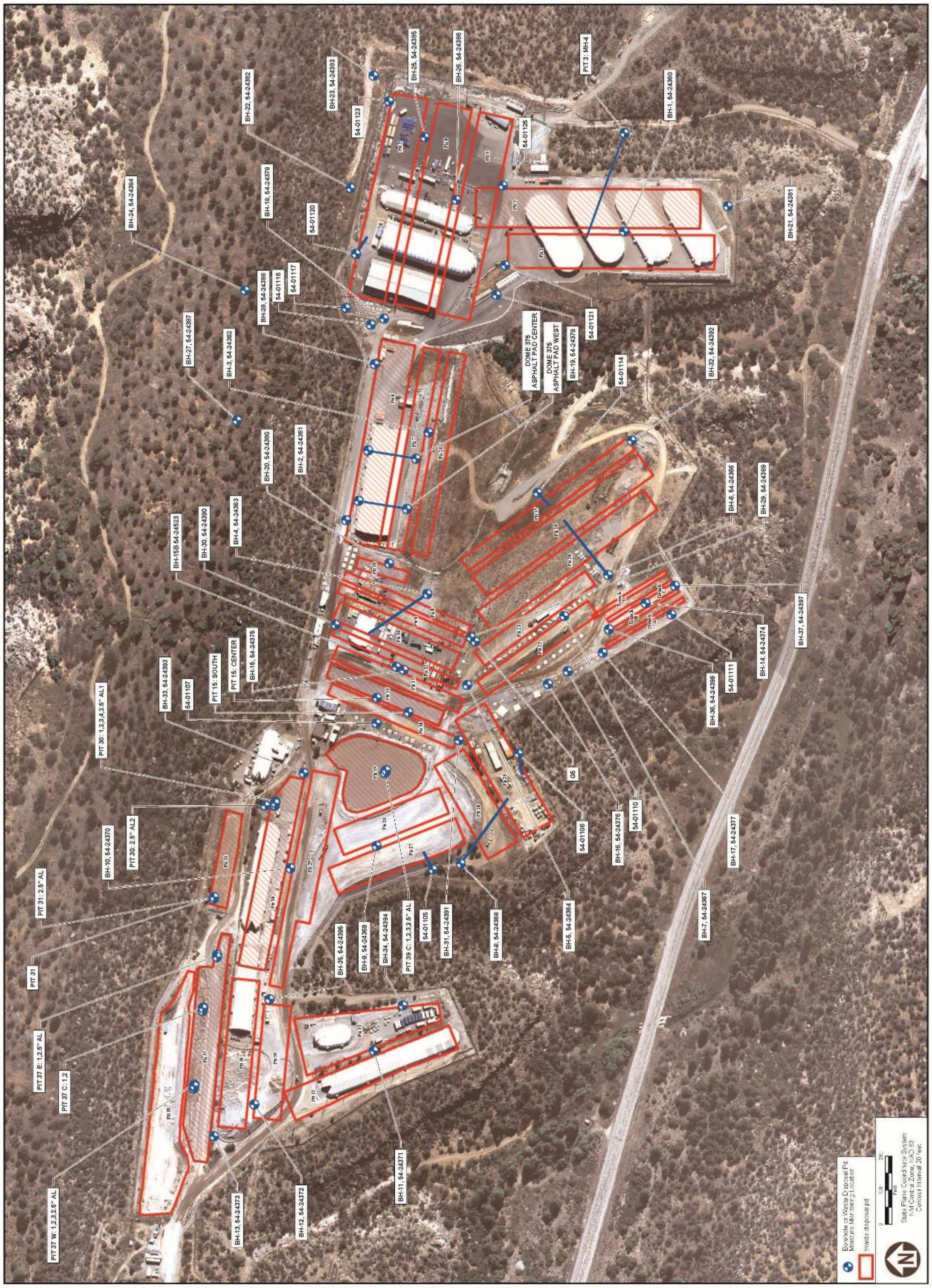


Figure 7. Locations of pits, structures, roads, and boreholes at Area G.

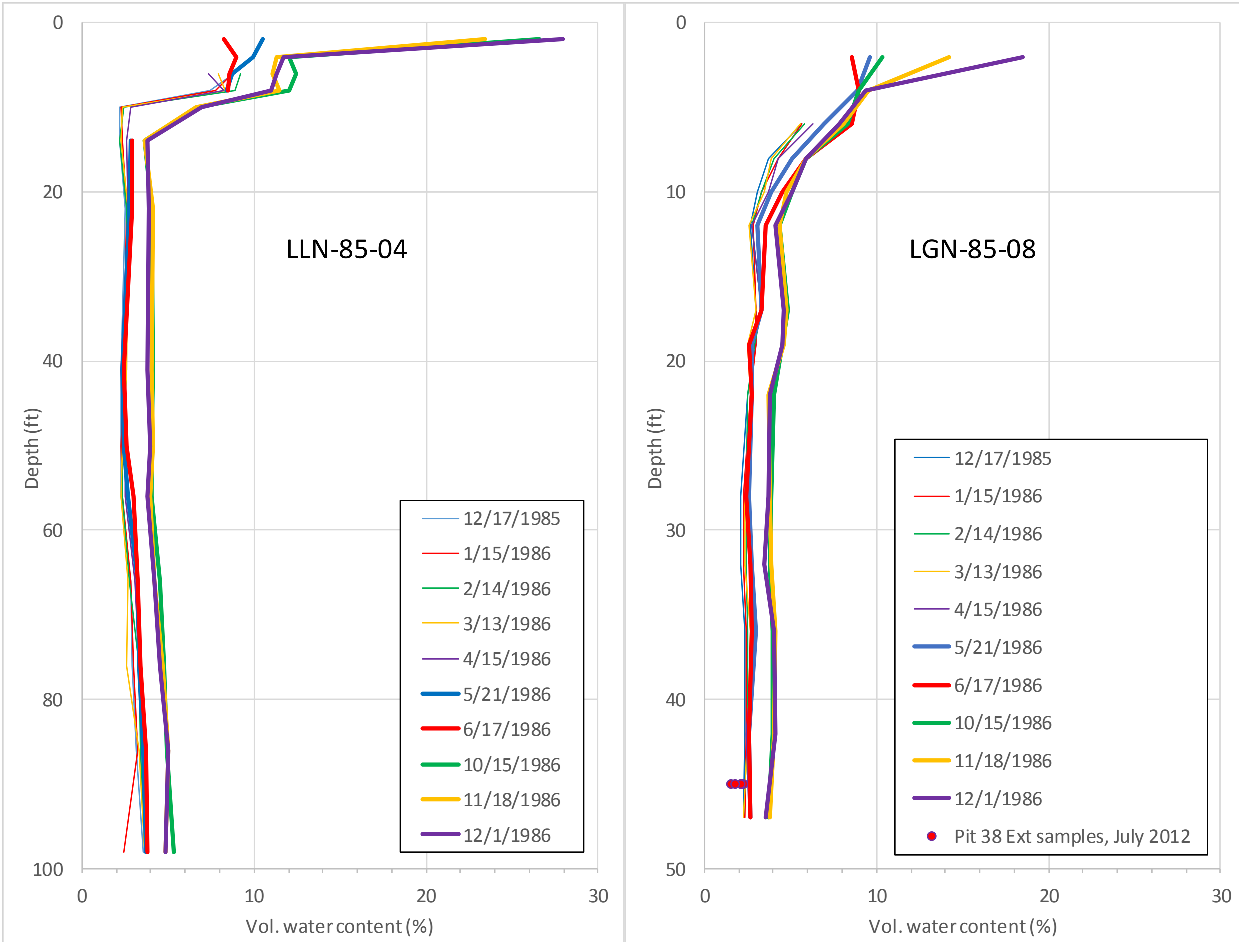


Figure 8. Water content profiles at LLN-85-04 and LGN-85-08 measured with a neutron probe. Water content samples collected from P38X are also shown.

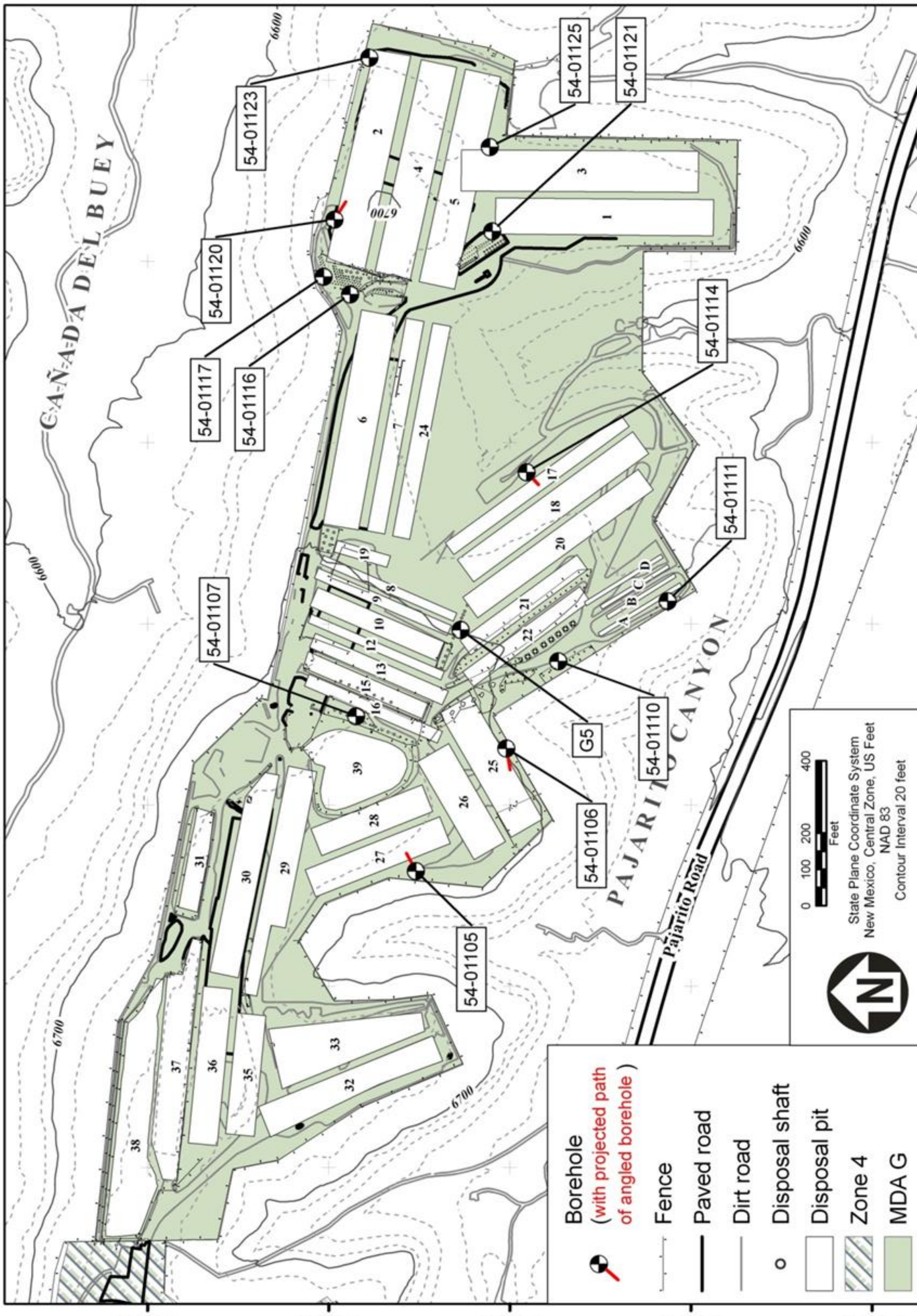


Figure 9. Locations of RFI boreholes (1100-Series) and G-5.

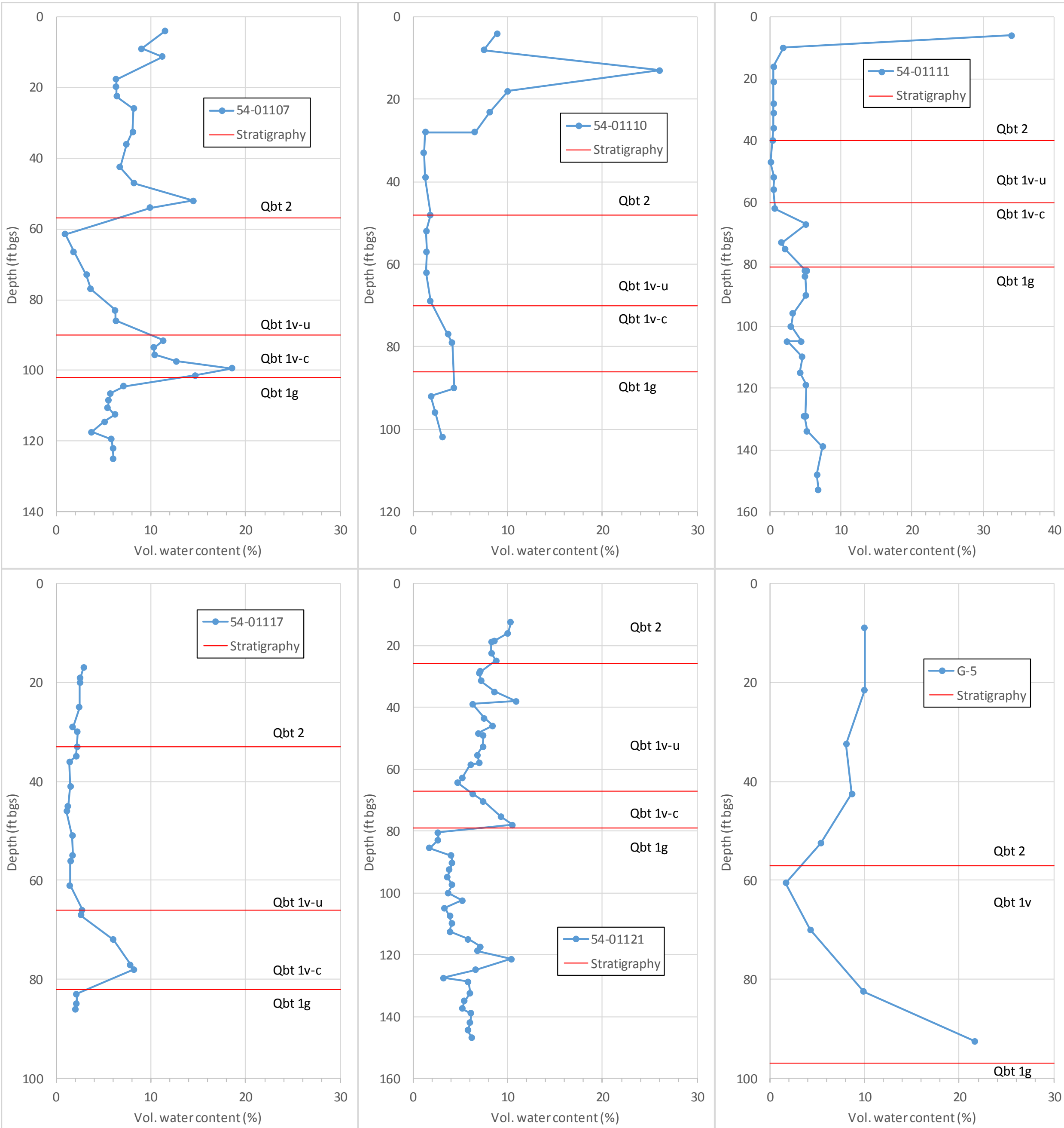


Figure 10. Water content profiles for 1994-1995 RFI boreholes, and 54-G-5.

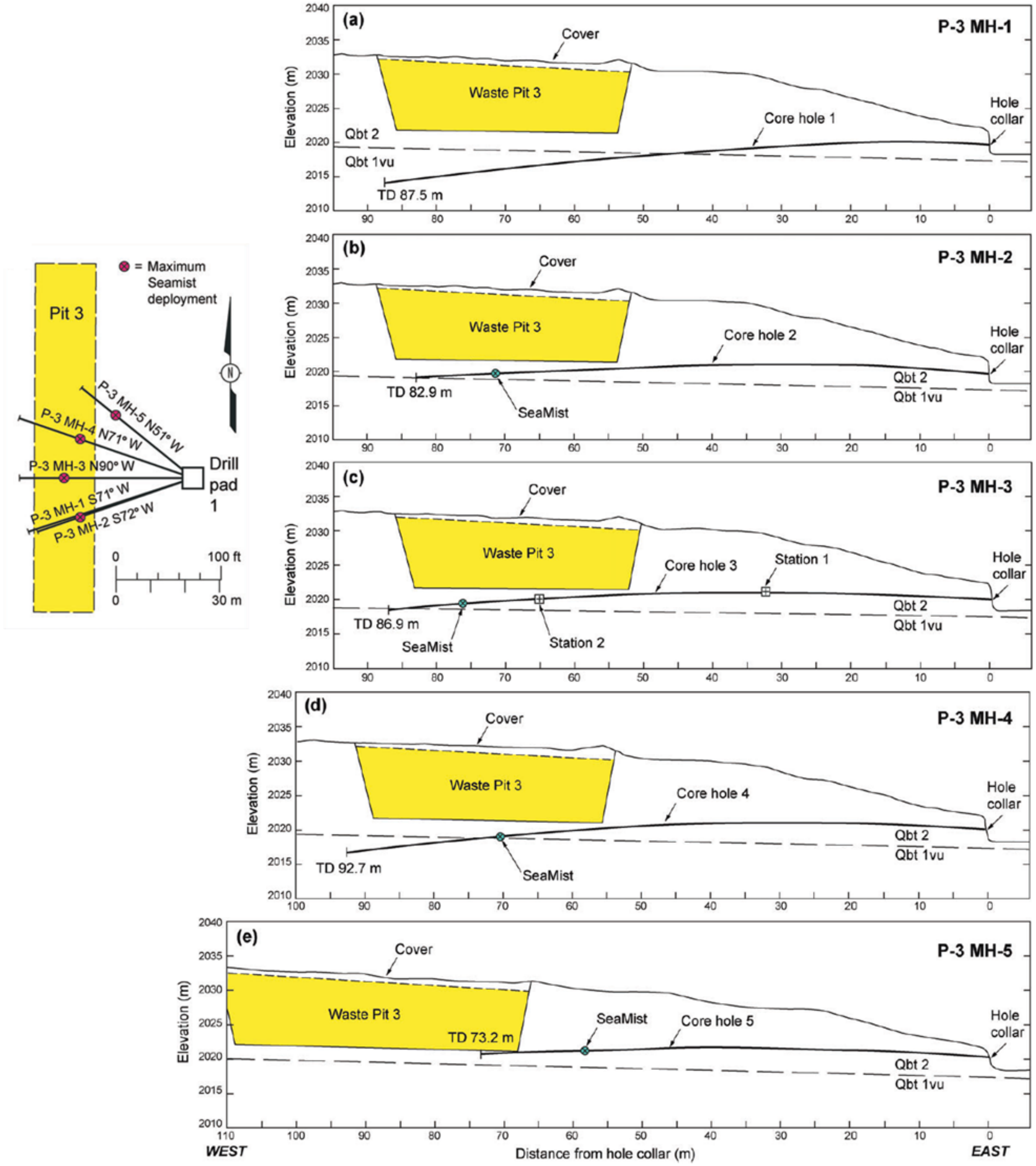


Figure 11. Profile view of boreholes P-3 MH-1 through MH-5 (from McLin et al., 2005). Plan view also shown on left.

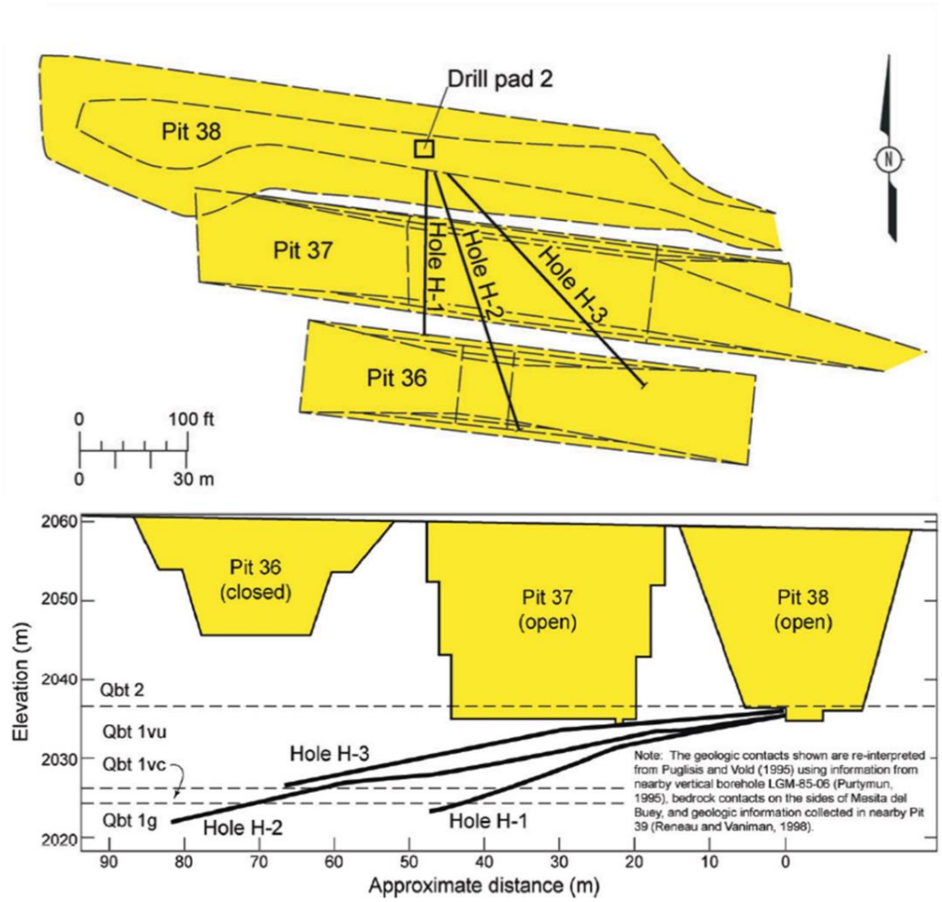


Figure 12. Plan view (top) and profile view (bottom) of boreholes H-1, H-2, H-3 drilled under Pits 37 and 36 (from McLin et al., 2005).

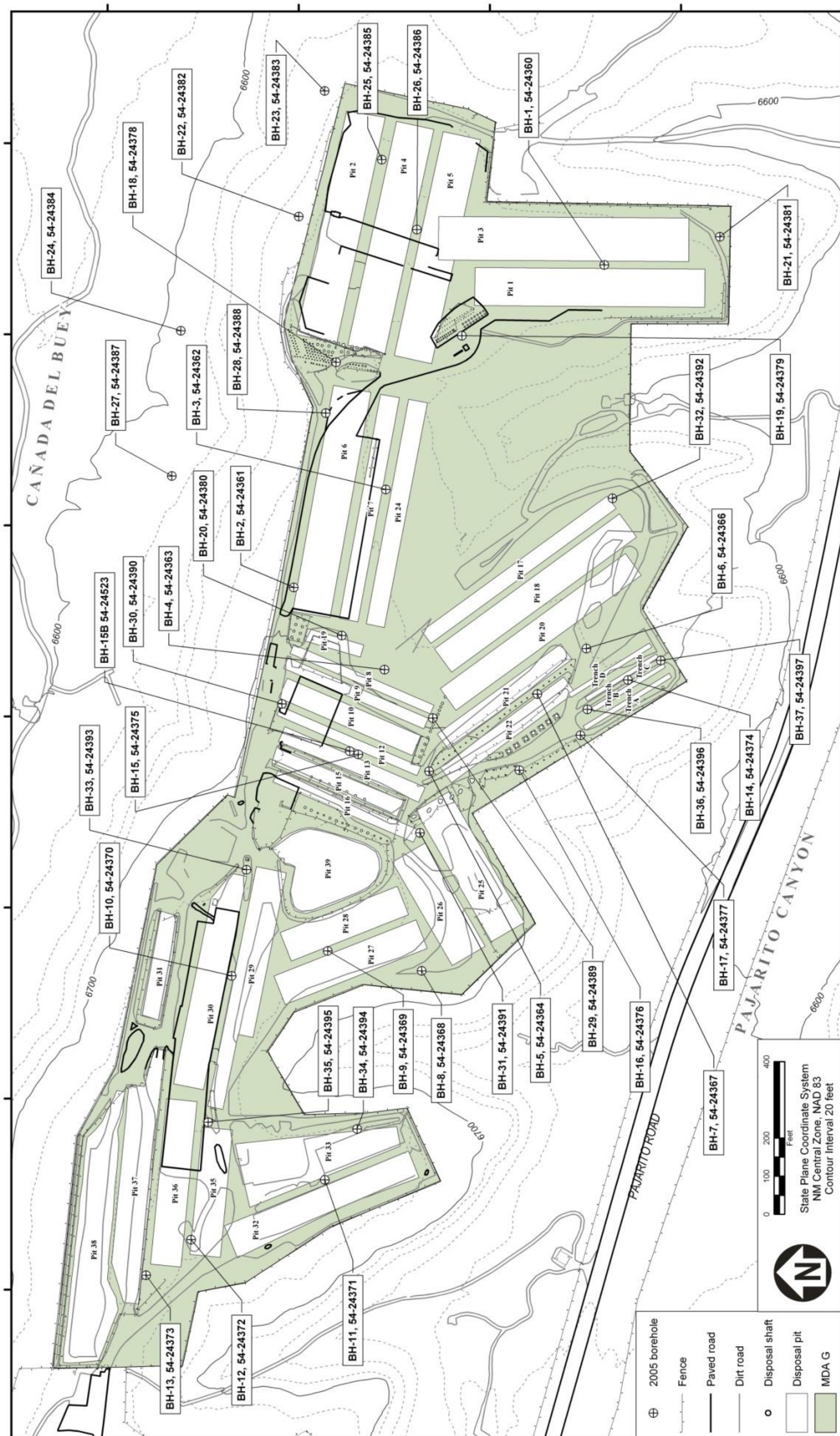


Figure 13. Locations of 2005 MDA G Investigation Report boreholes.

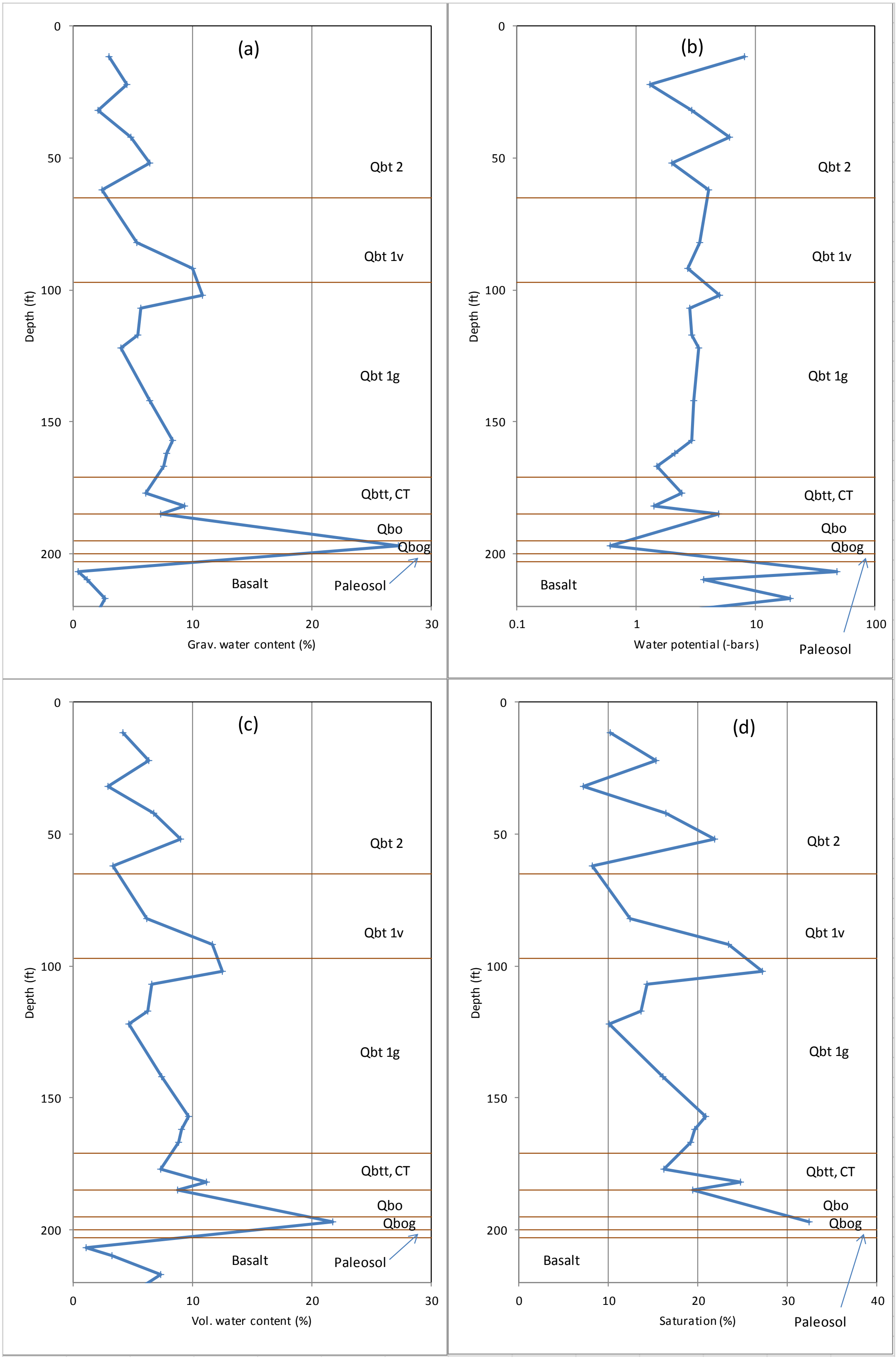


Figure 14. Measured gravimetric water content (a), water potential (b), and calculated volumetric water content (c), and saturation (d) from core collected at boreholes BH-15-2.

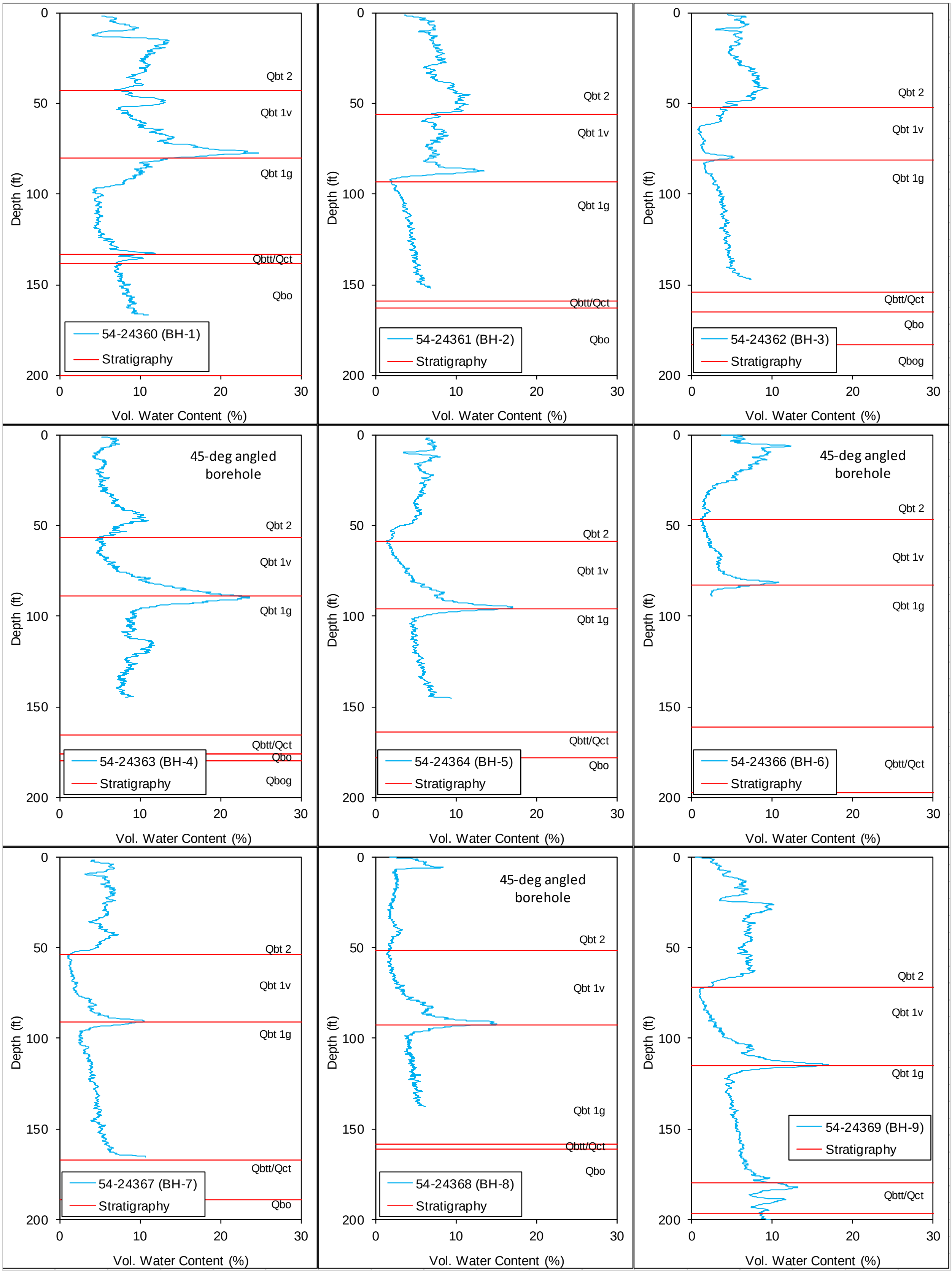


Figure 15. Water content profiles for 2005 IR boreholes BH-1 to BH-9.

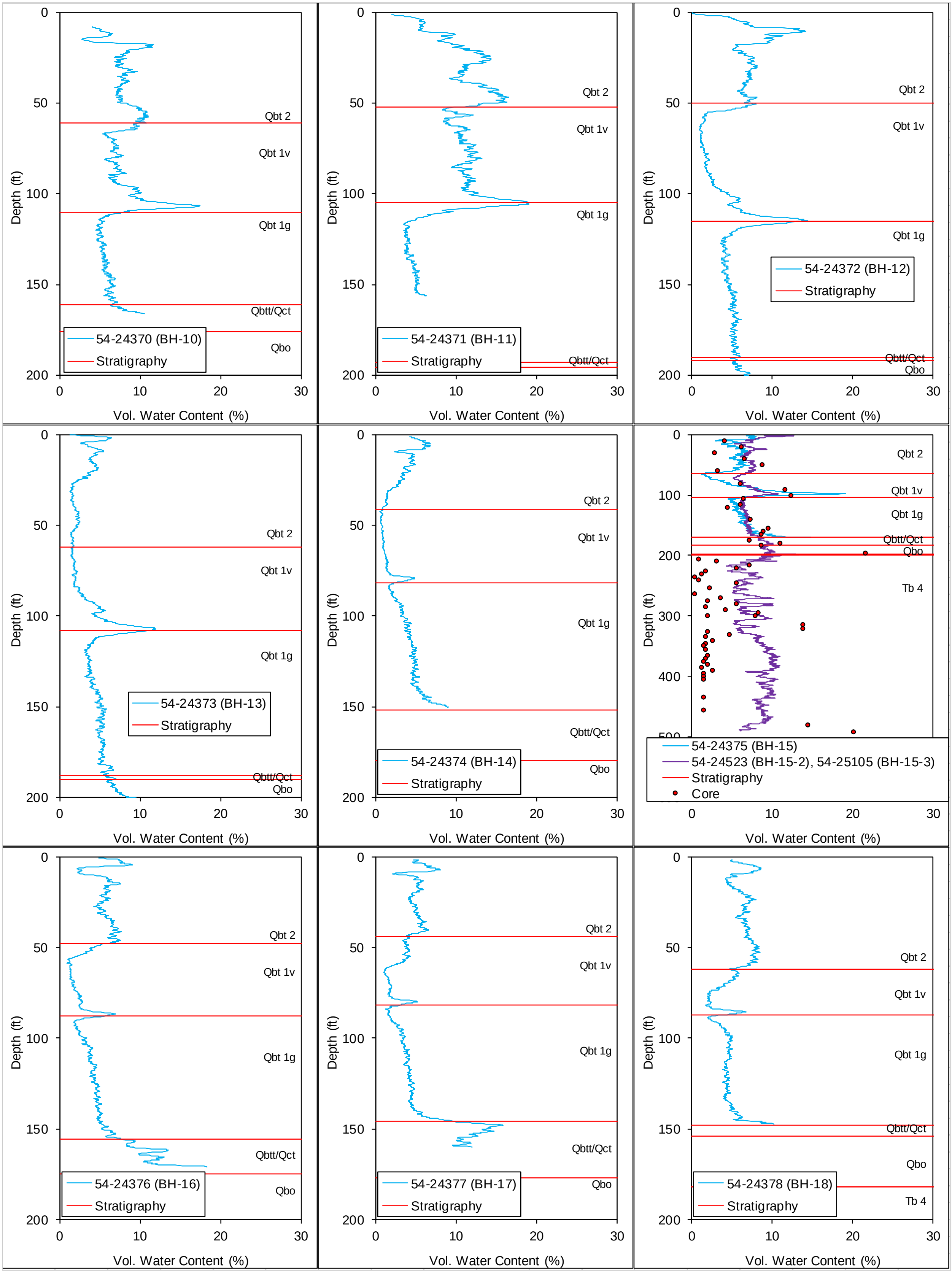


Figure 16. Water content profiles for 2005 IR boreholes BH-10 to BH-18.

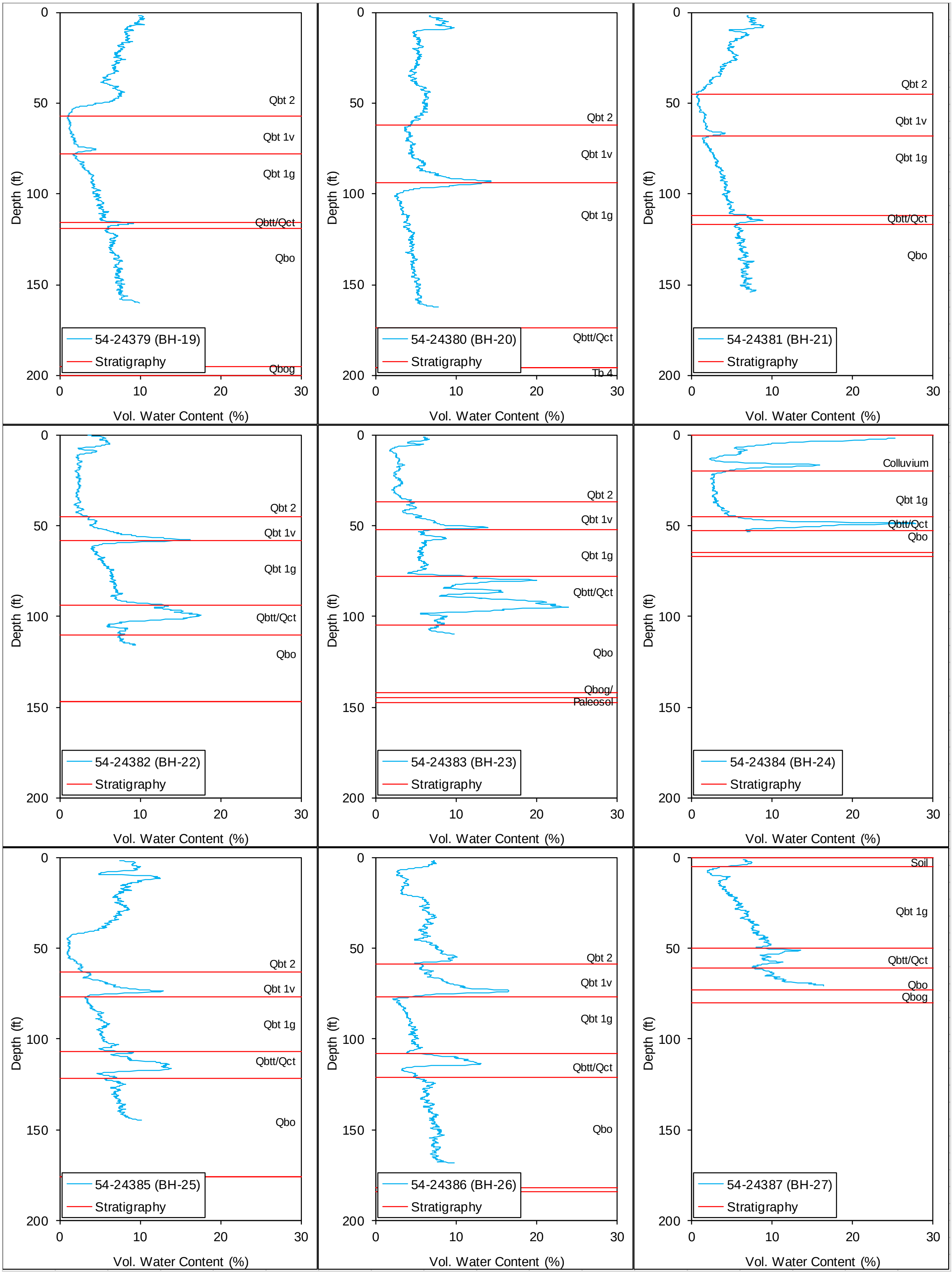


Figure 17. Water content profiles for 2005 IR boreholes BH-19 to BH-27.

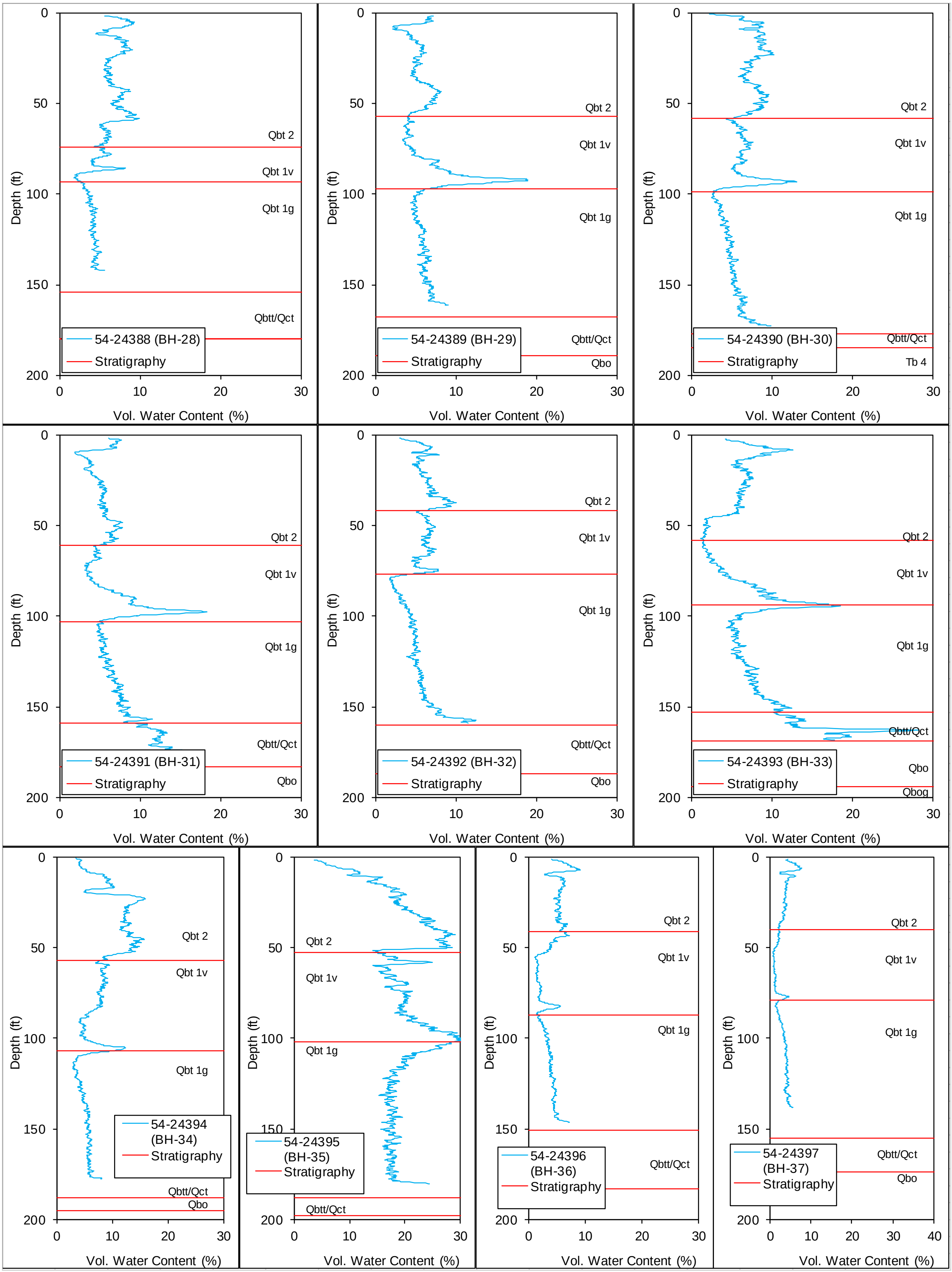


Figure 18. Water content profiles for 2005 IR boreholes BH-28 to BH-37.

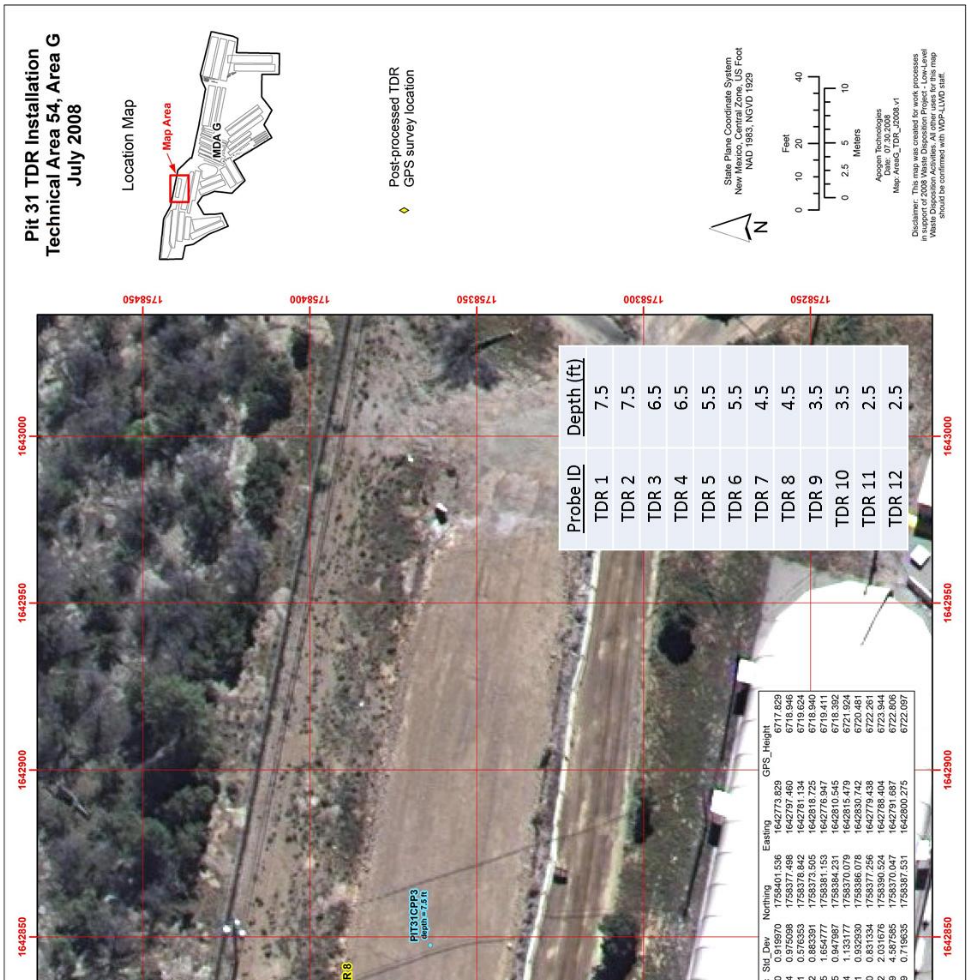


Figure 19. Locations of TDR probes in Pit 31 ET cover.

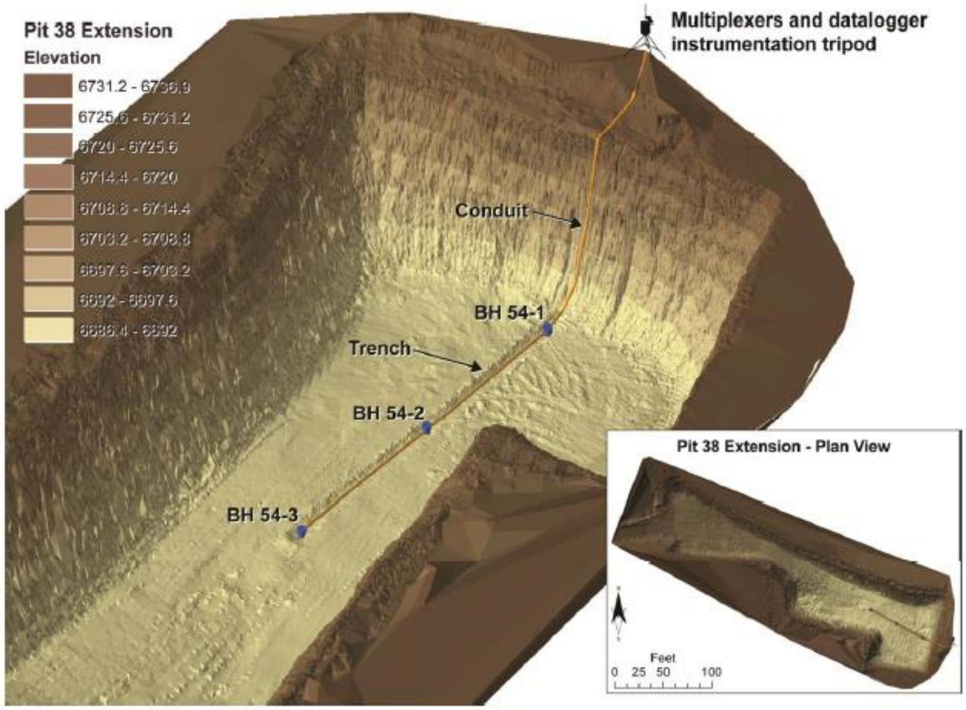


Figure 20. Three-dimensional view of eastern half of P38X, 3 HDP boreholes, HDP sensor cable, and PVC conduit routing.

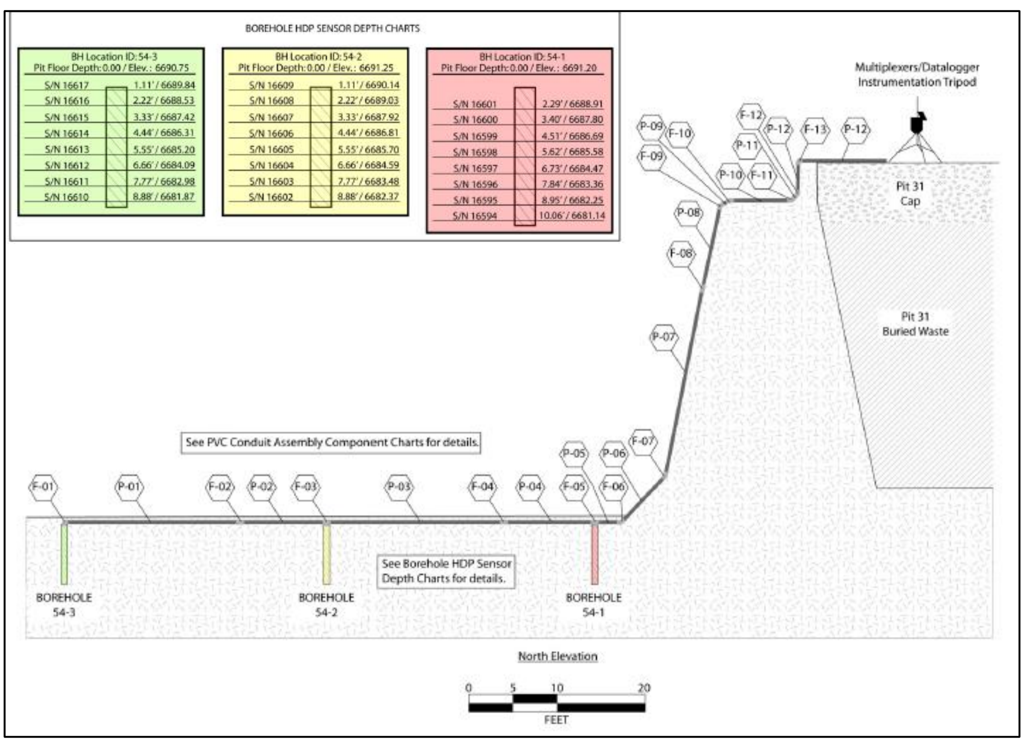


Figure 21. Schematic cross-section diagram of HDP installation in P38X. Boreholes 54-1, 54-2, and 54-3 are also known as East, Center, and West HDP boreholes, respectively. [Note: P- and F- symbols denote PVC conduit components.]

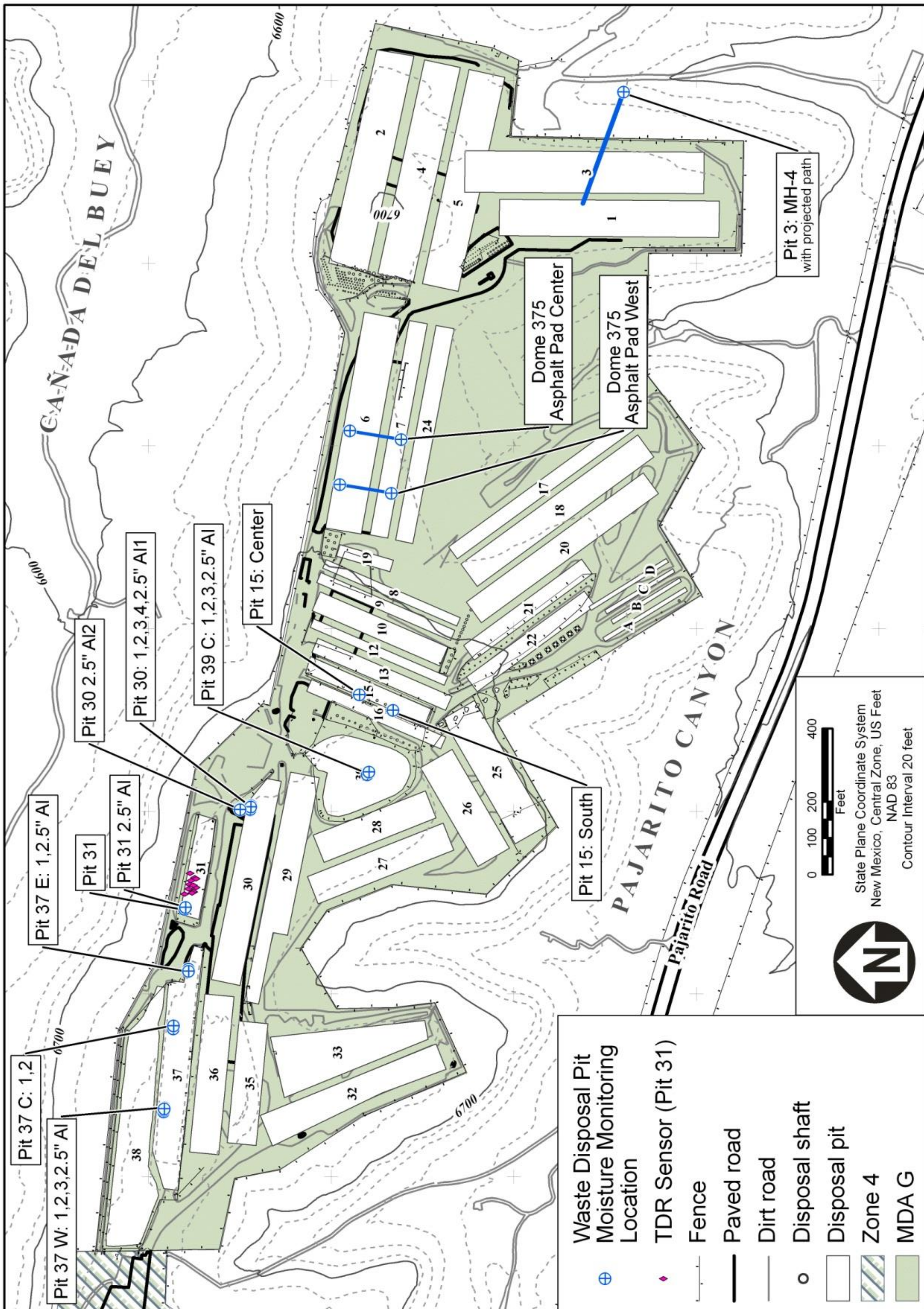


Figure 22. Waste pit monitoring locations at Dome 375, P-3 MH-4, and in Pits 15, 30, 31, and 37.

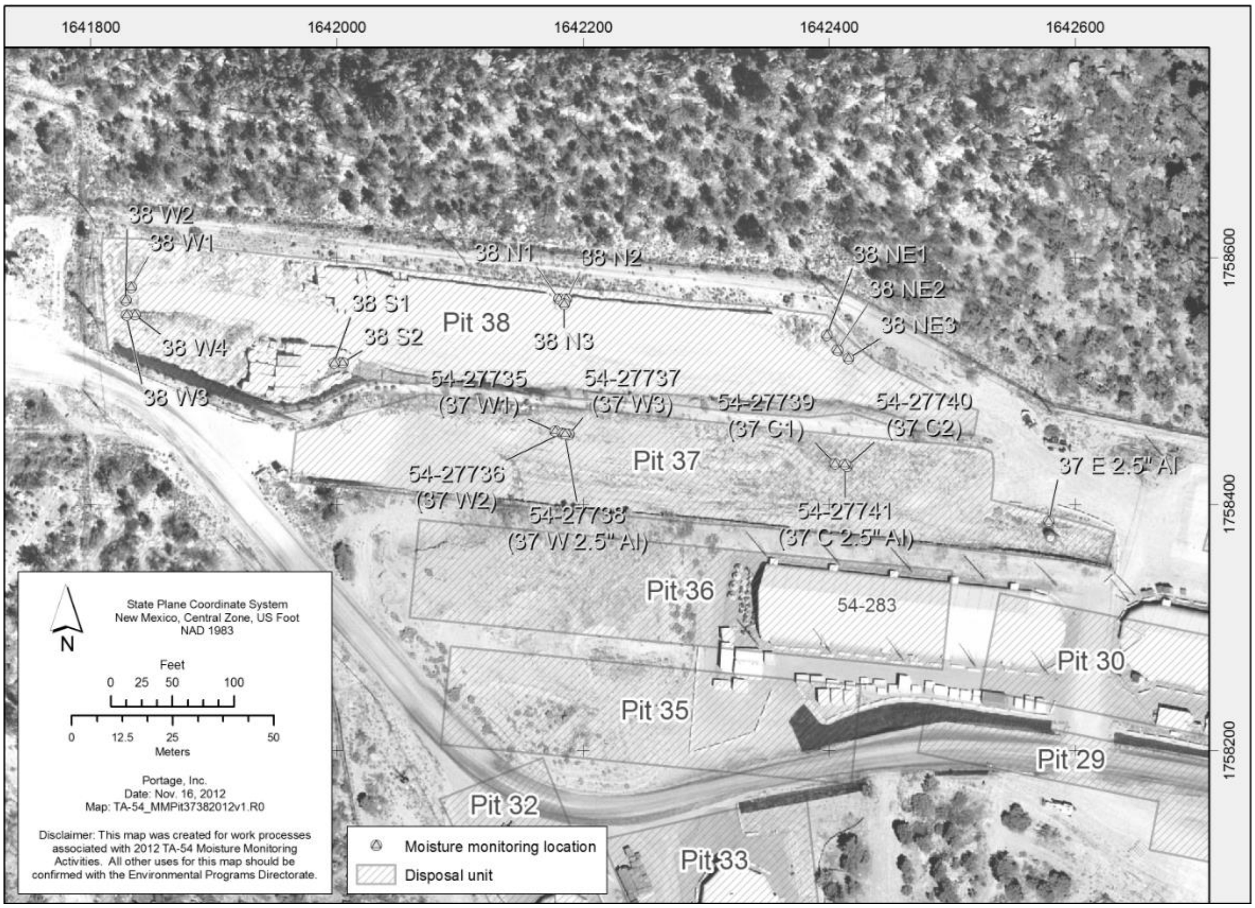


Figure 23. Waste pit monitoring locations in Pit 37 and 38.

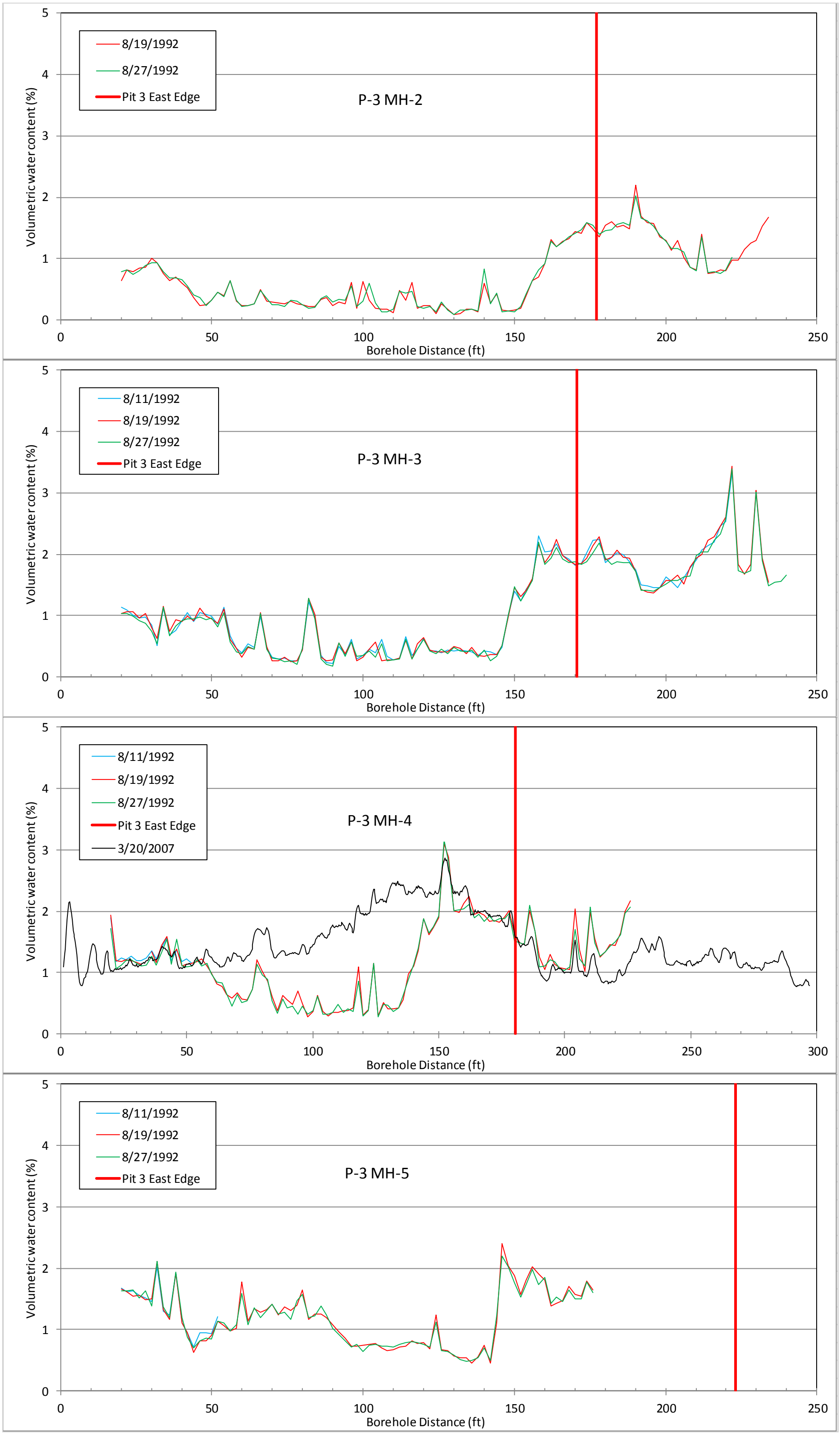


Figure 24. Water content profiles at Medusa boreholes. Borehole distance increases from east to west.

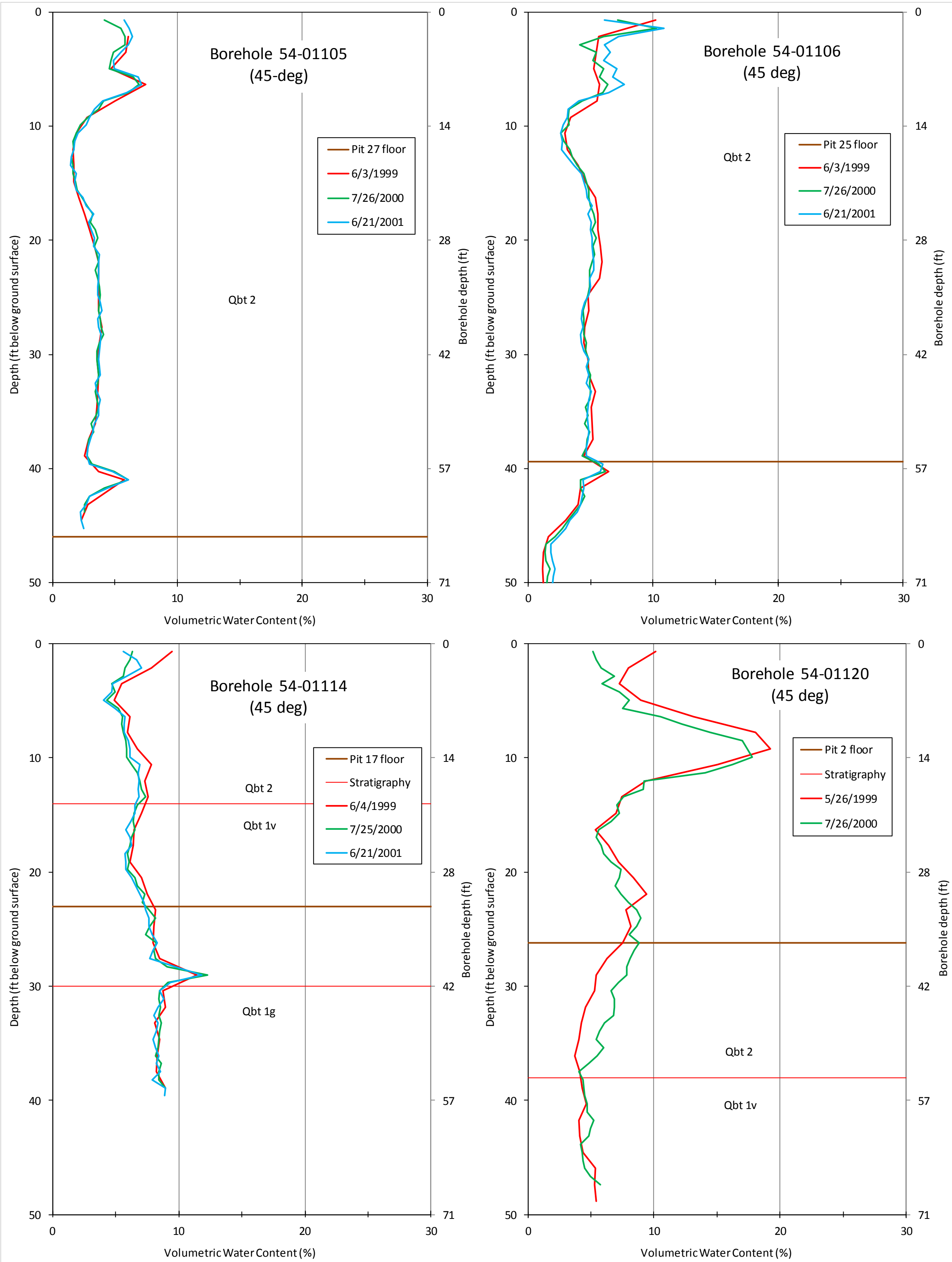


Figure 25. Water content profiles for angled boreholes 54-01105, 54-01106, 54-01114, and 54-01120.

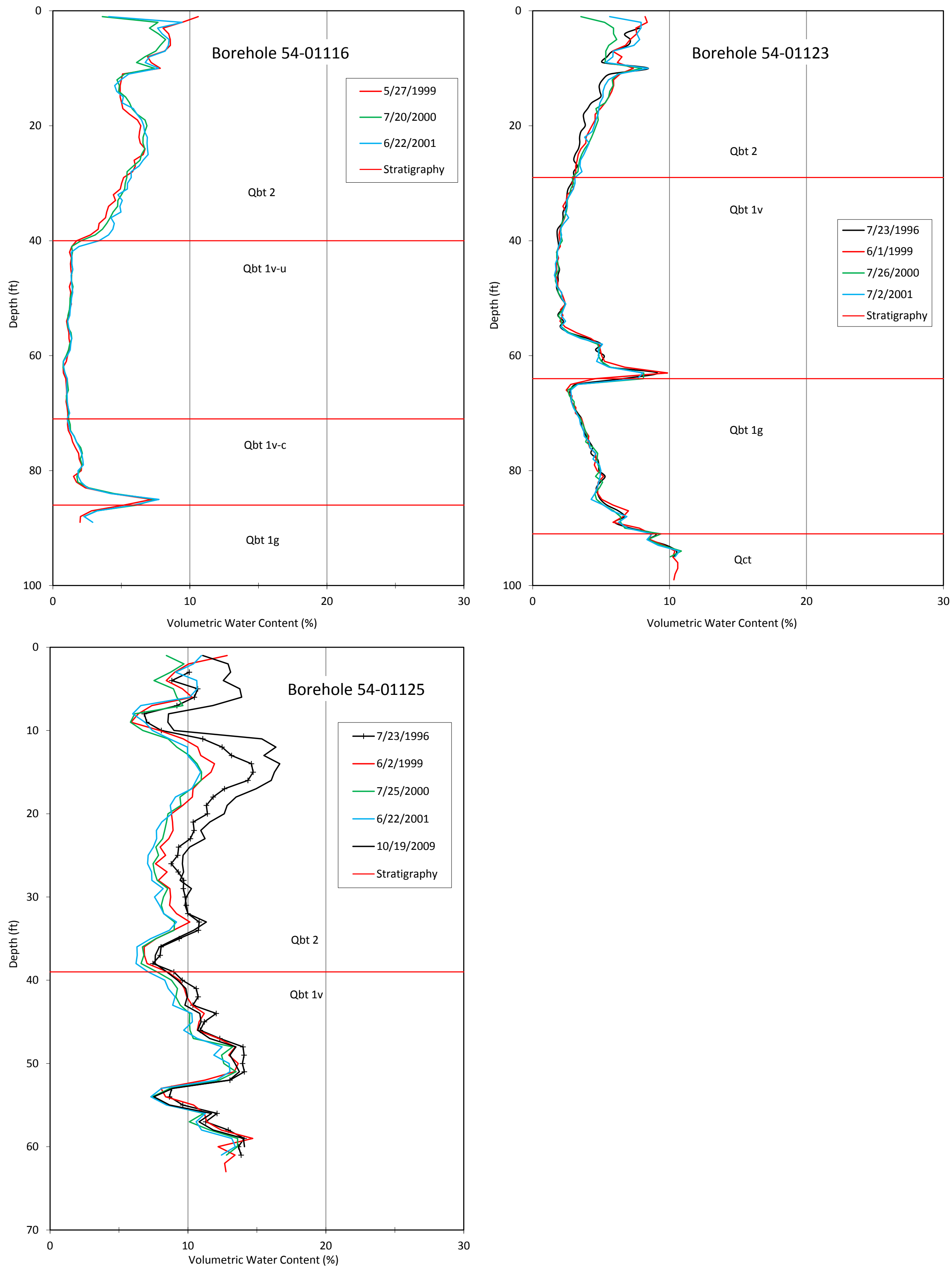


Figure 26. Water content profiles for vertical boreholes 54-01116, 54-01123, and 54-01125.

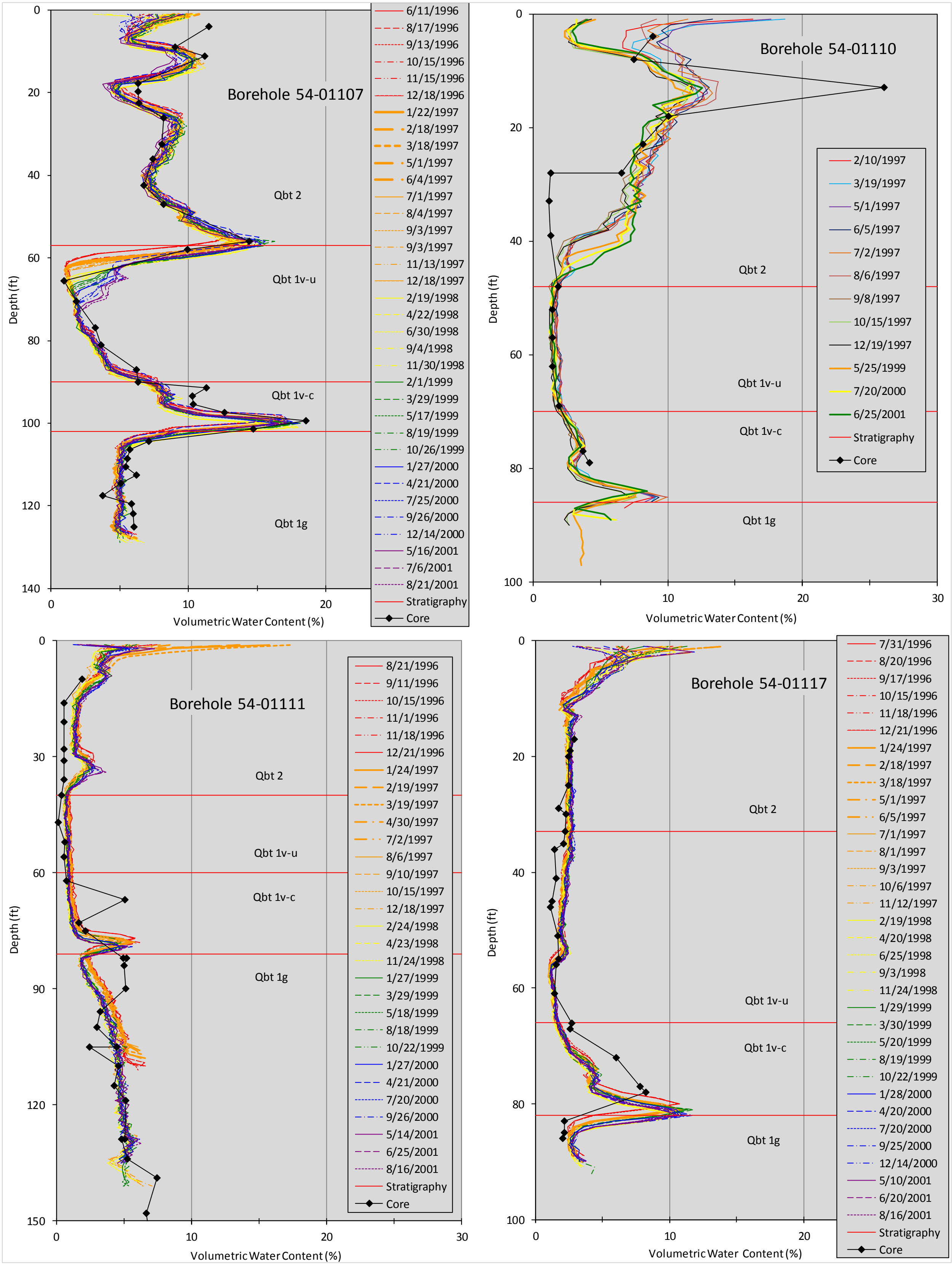


Figure 27. Water content profiles for vertical boreholes 54-01107, 54-01110, 54-01111, and 54-01117.

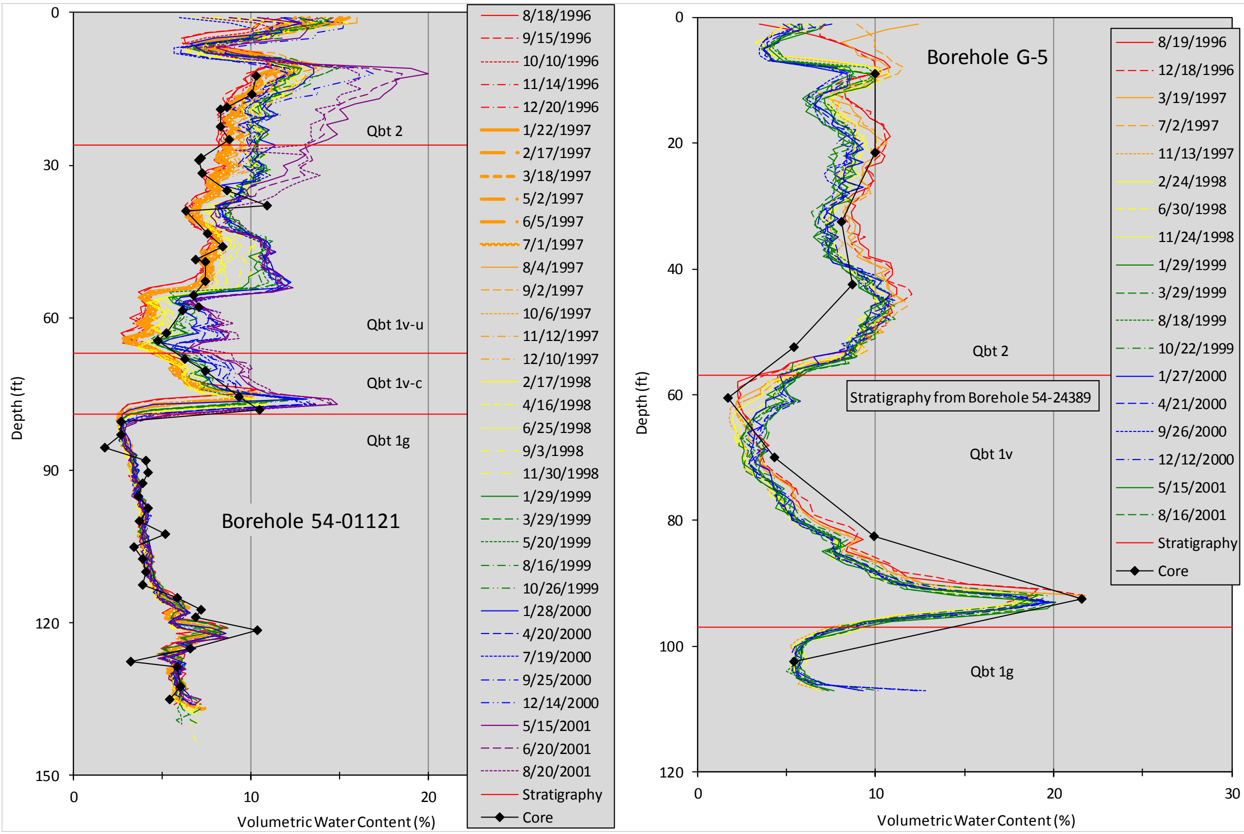


Figure 28. Water content profiles for vertical boreholes 54-01121, and G-5.

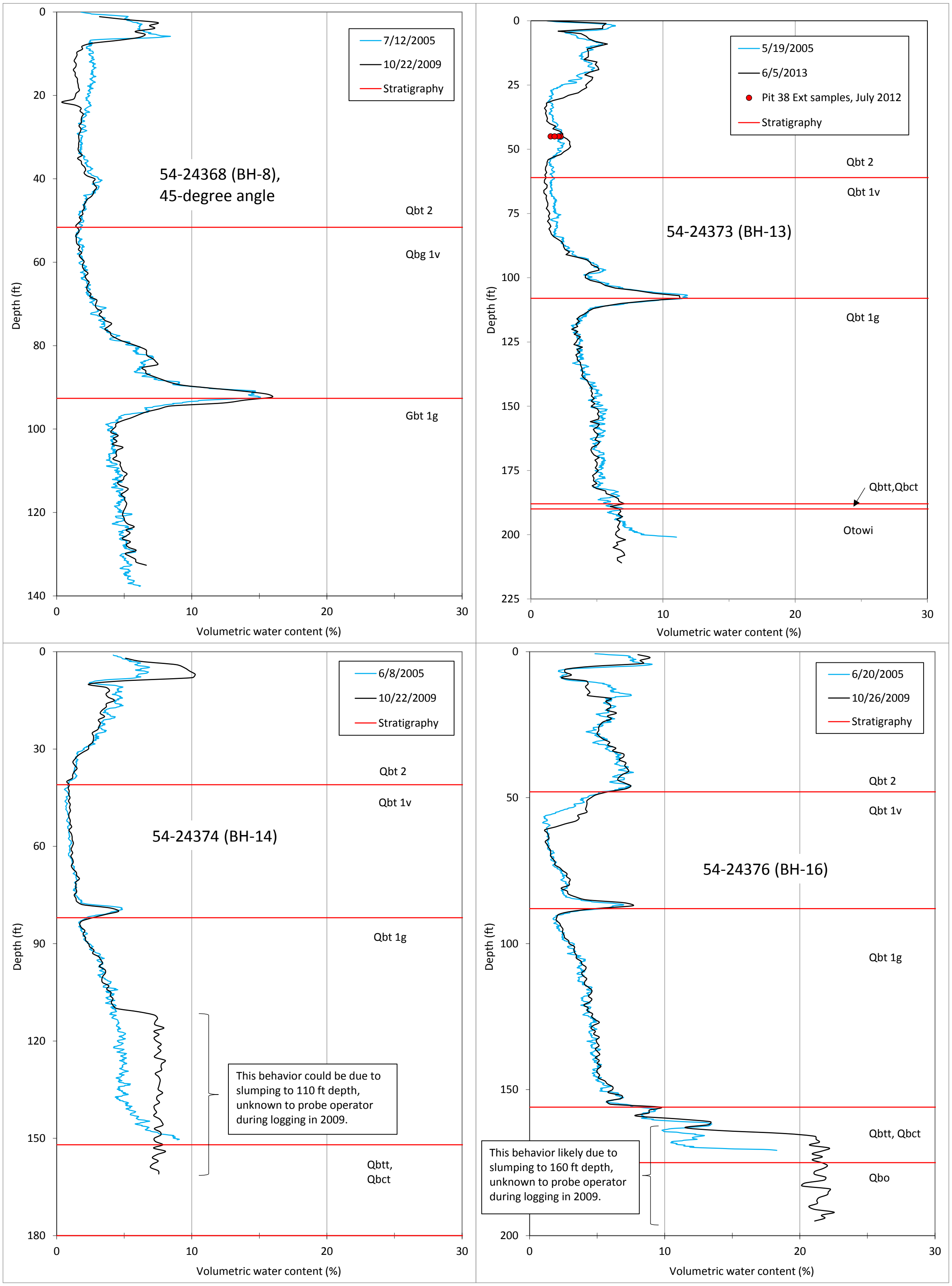


Figure 29. Water content profiles for 2005 IR boreholes that have been logged since 2005 (1).

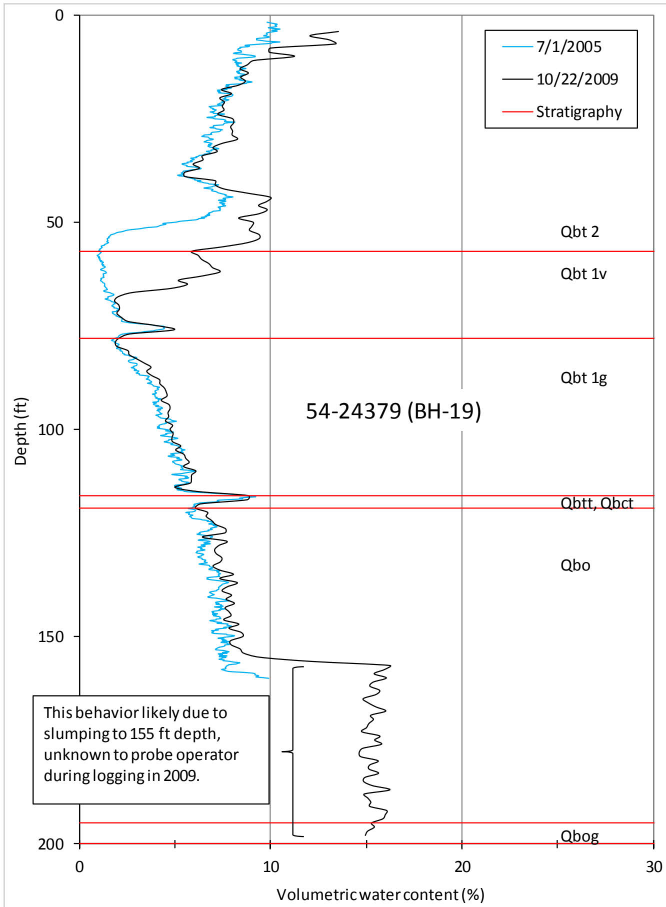


Figure 30. Water content profiles for 2005 IR boreholes that have been logged since 2005 (2).

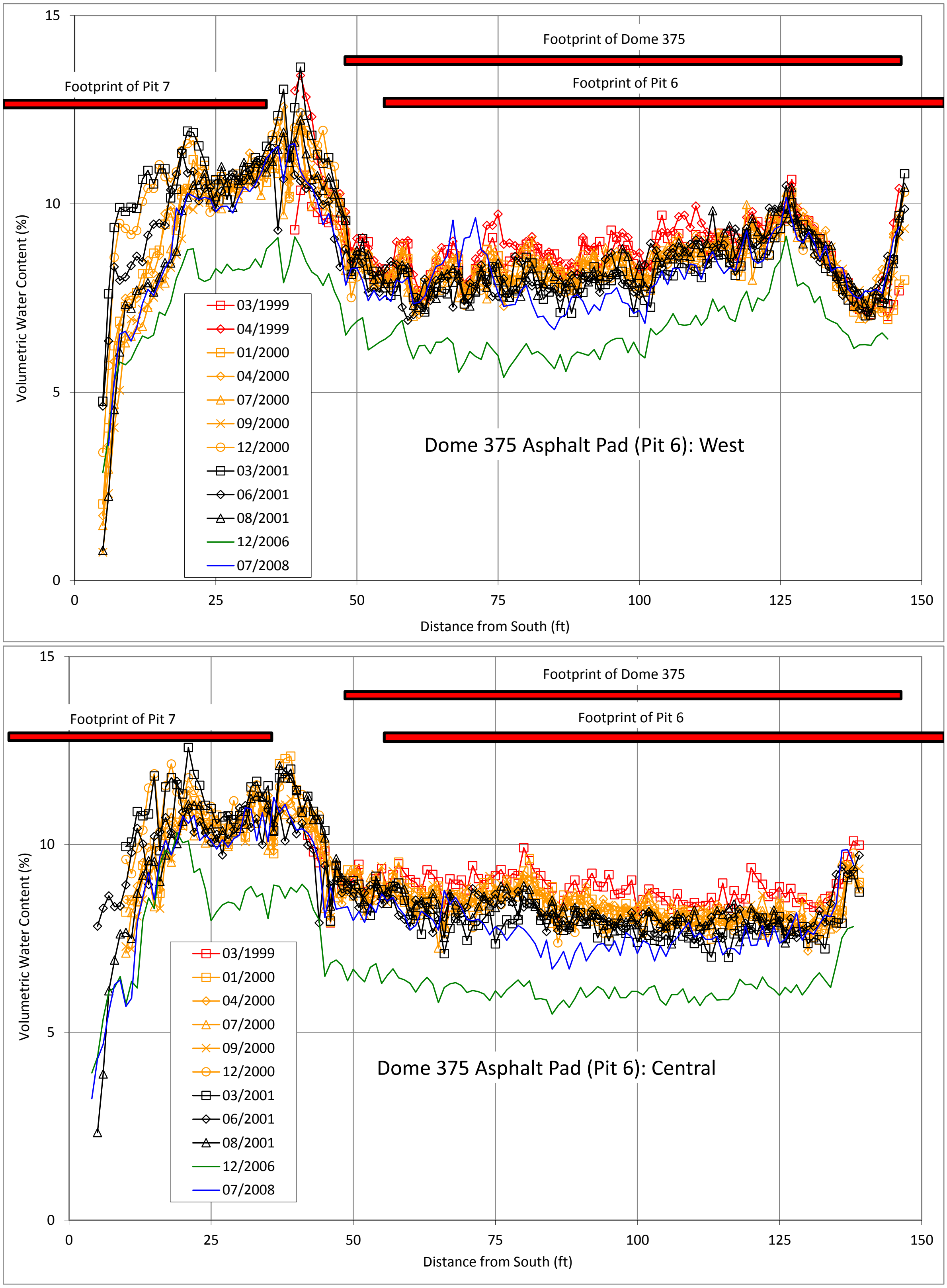


Figure 31. Horizontal water content profiles measured in Dome 375 West (top) and Central (bottom) access tubes.

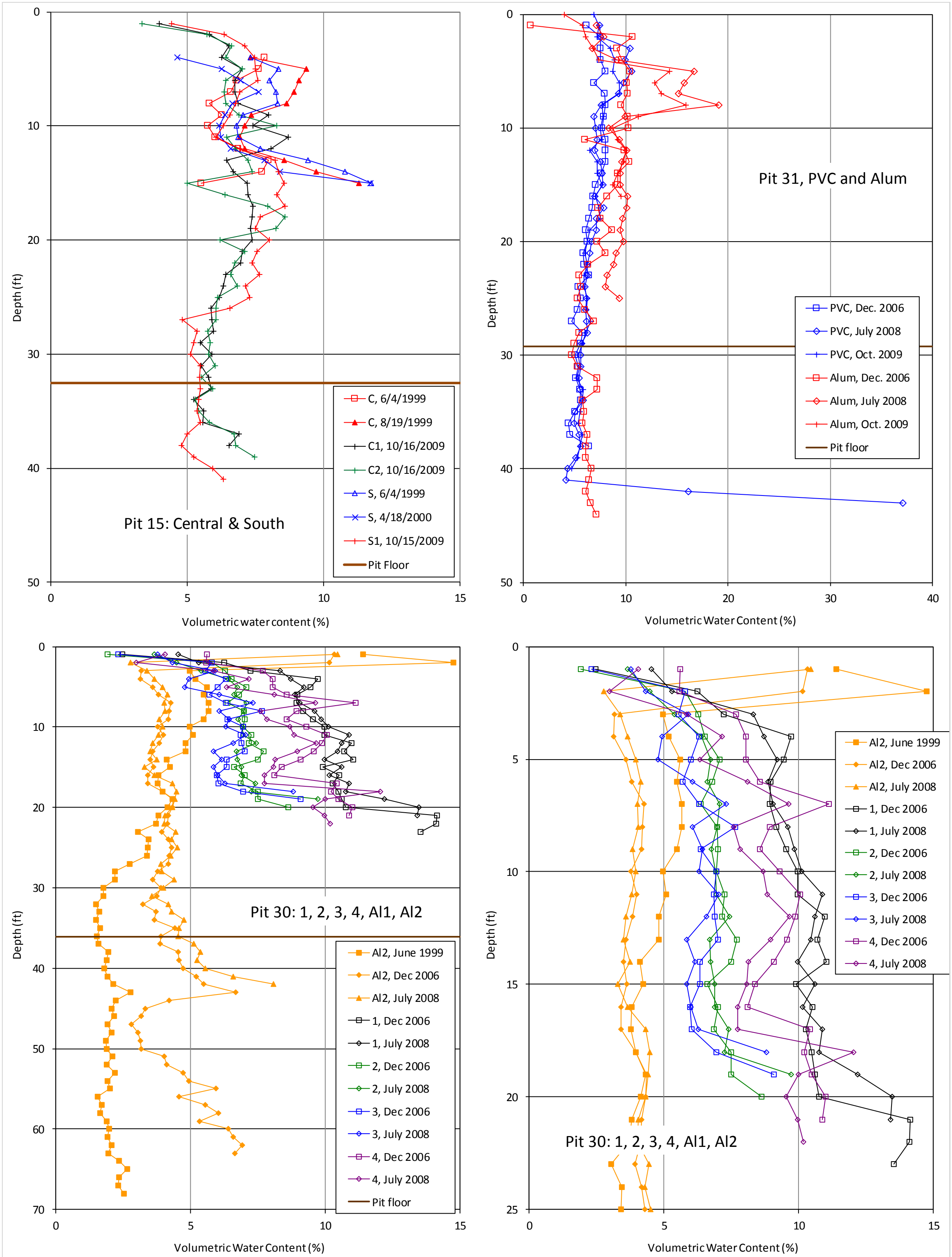


Figure 32. Water content profiles measured in Pit 15 and 31 (top) and Pit 30 (bottom) access tubes. The two Pit 30 profiles have different y-axis scales.

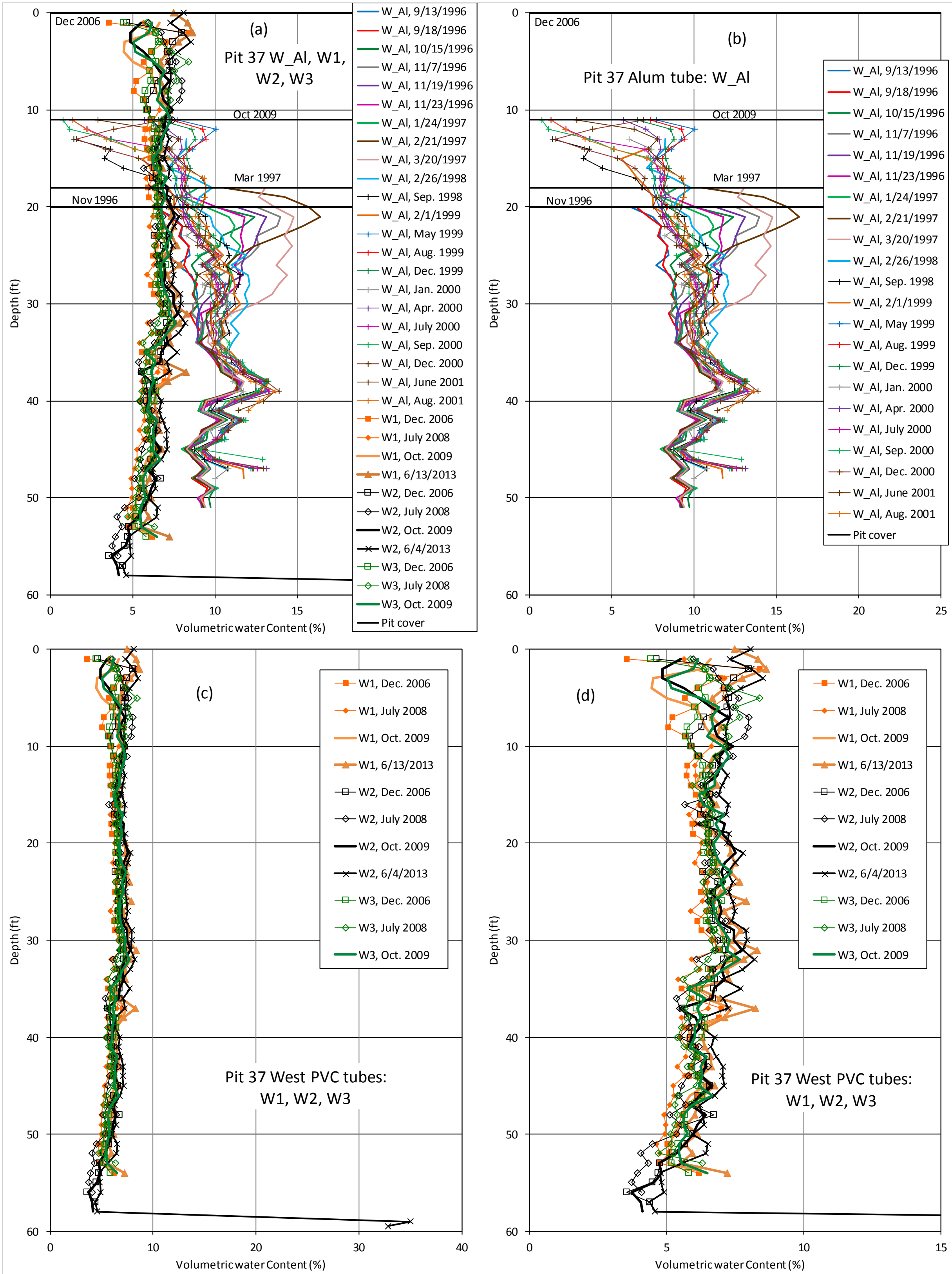


Figure 33. Water content profiles measured in Pit 37W access tubes: (a) all data; (b) W_Al only; (c) PVC tubes only; and (d) same as (c) with reduced x-axis.

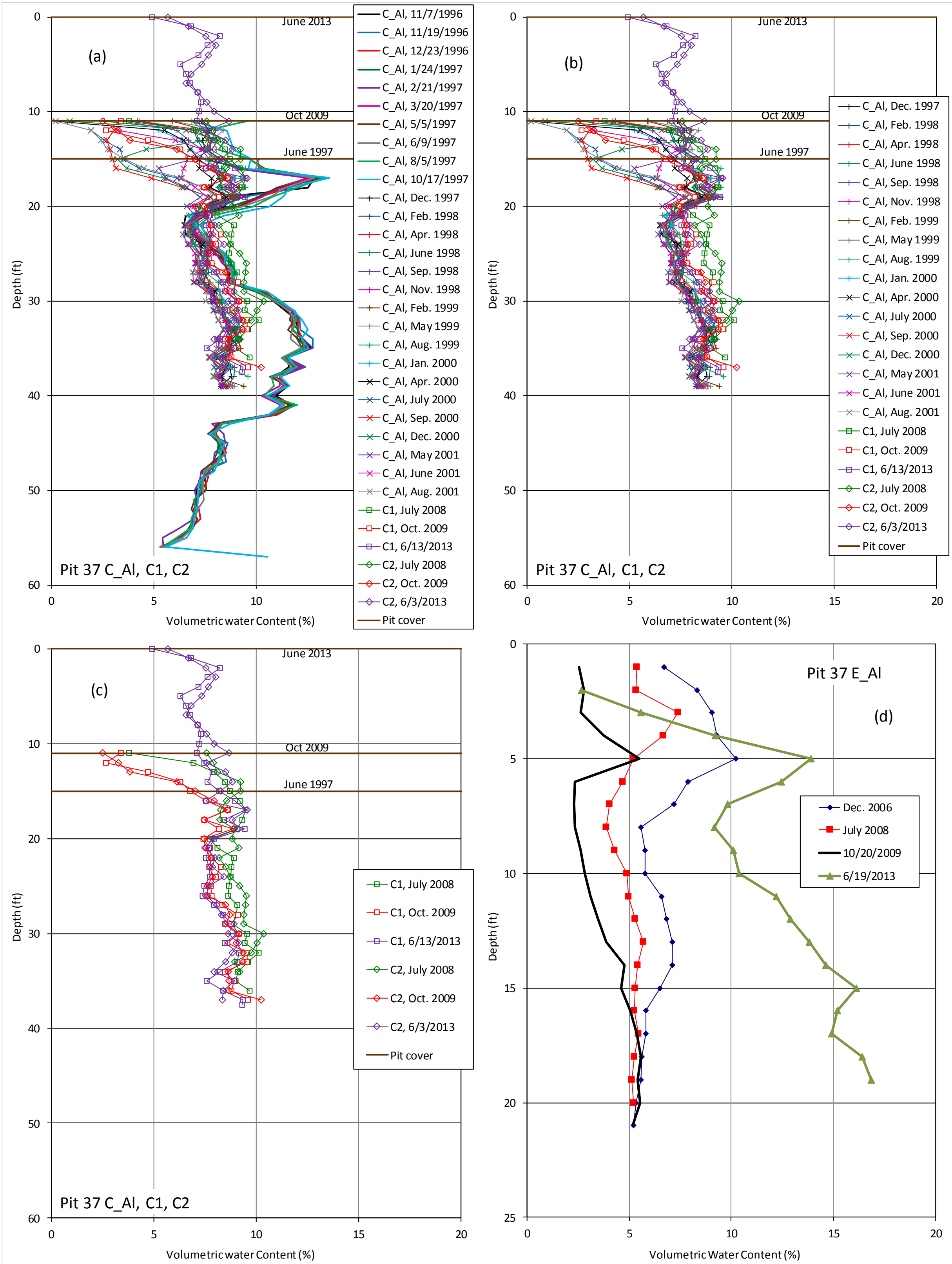


Figure 34. Water content profiles measured in Pit 37C (a), (b), and (c) and 37E access tubes (d). Horizontal, dated lines indicate level of waste/fill in the operating pit.

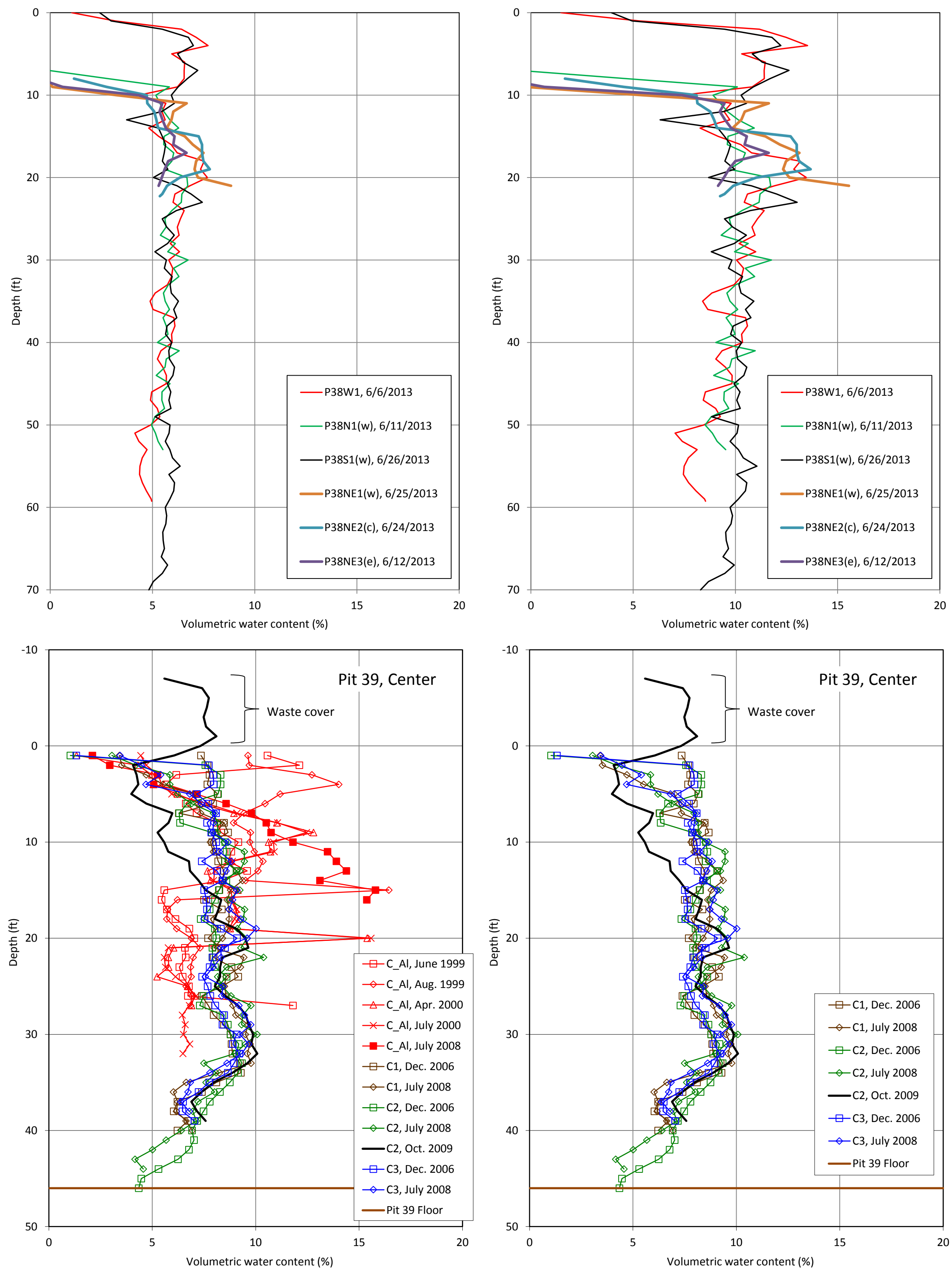
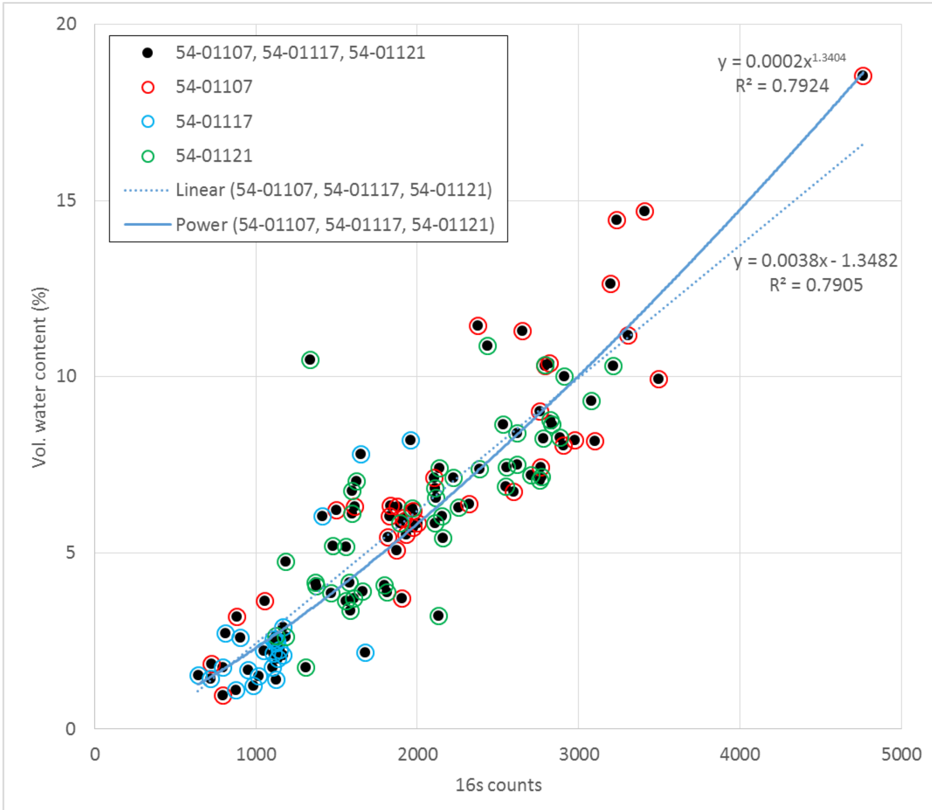


Figure 35. Water content profiles measured in Pit 38 (top) and Pit 39 (bottom) access tubes. Pit 38 profiles shown using Loaiza & Vold (1995) calibration (left) and using schedule-80 correction (right). Pit 39 profiles shown with (left) and without (right) data from aluminum tubes.



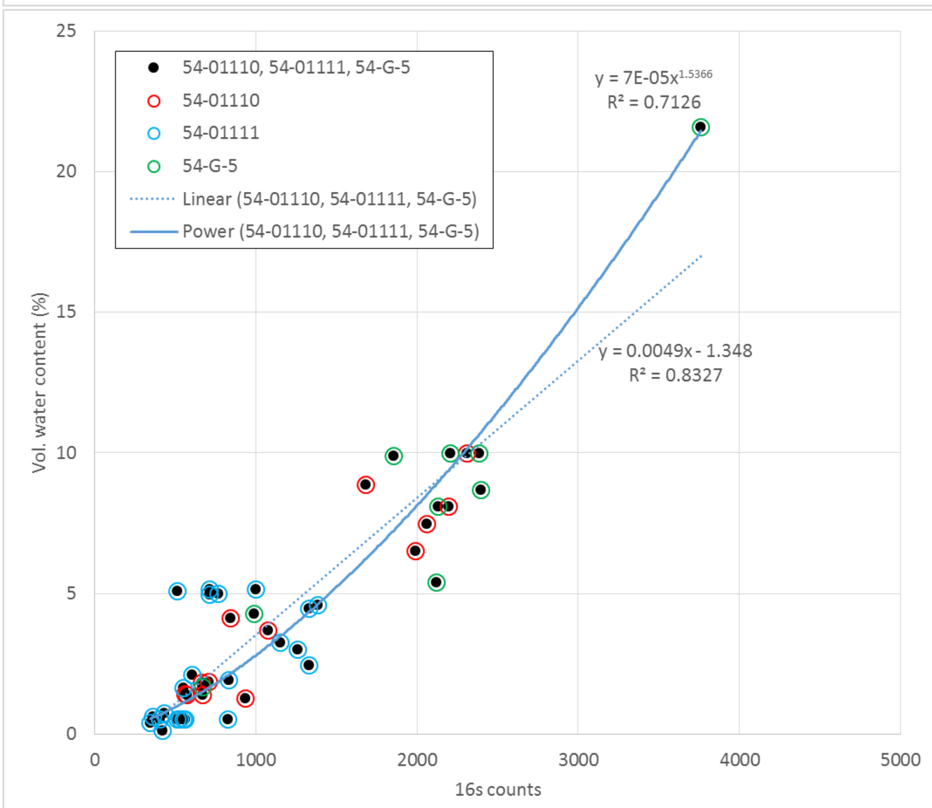


Figure 36. Calibrations for 4.5-in (top) and 6-in (bottom) uncased boreholes.

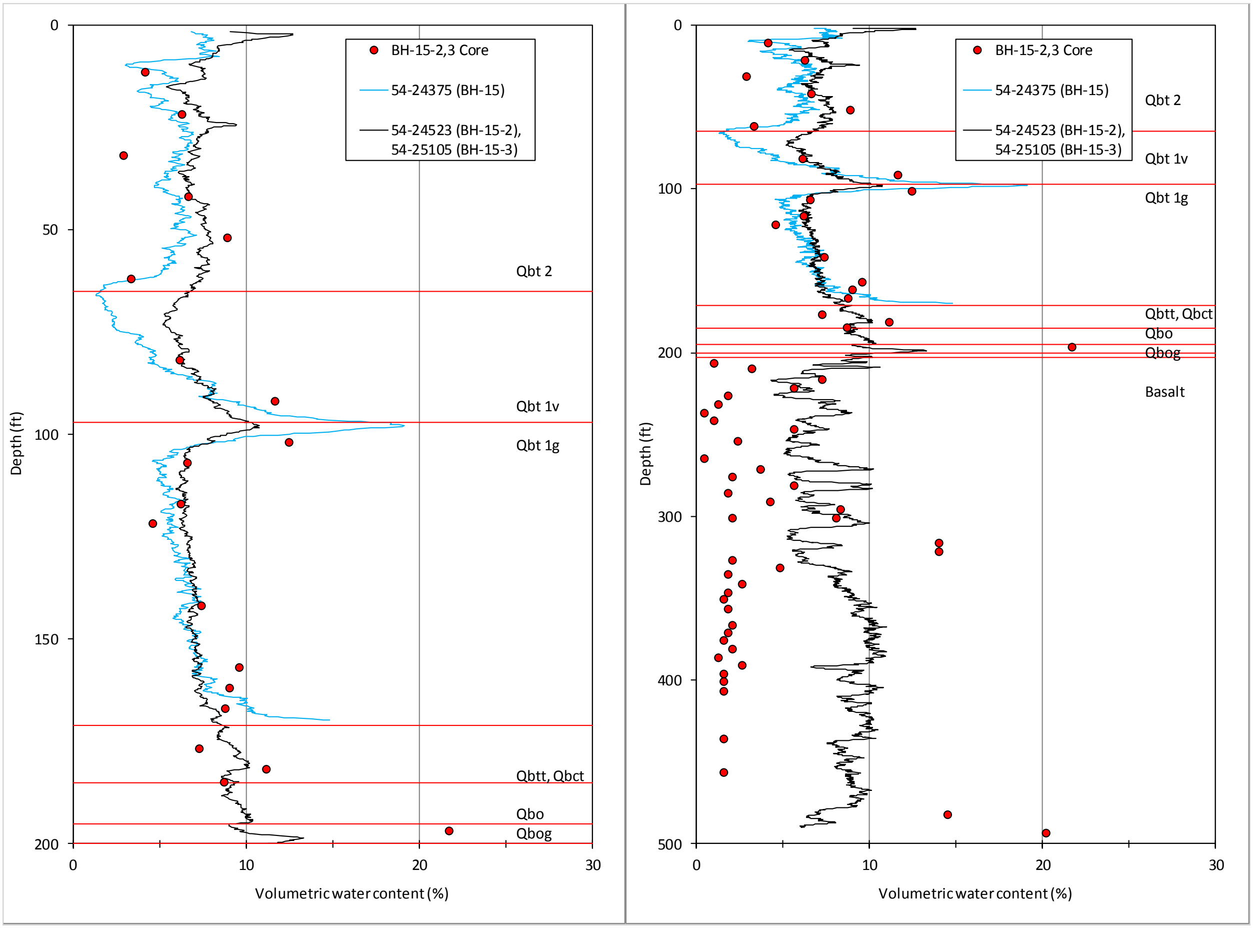


Figure 37. Water content profiles (neutron logs and core) in BH-15, BH-15-2 and BH-15-3. Left figure shows profile to depth of 200 ft while right figure shows depth to 500 ft.

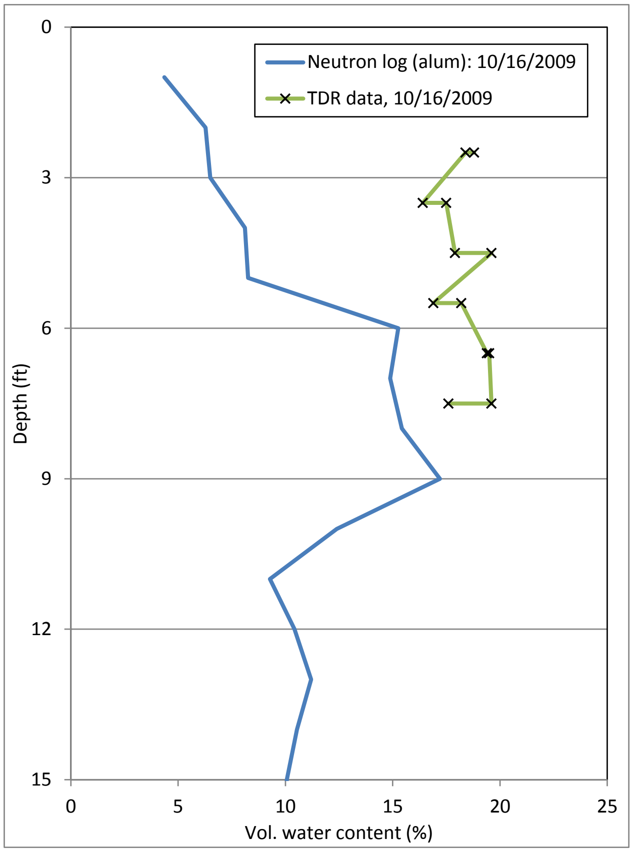


Figure 38. Comparison of water content profile measured by neutron probe and TDR probes in the cover of Pit 31.

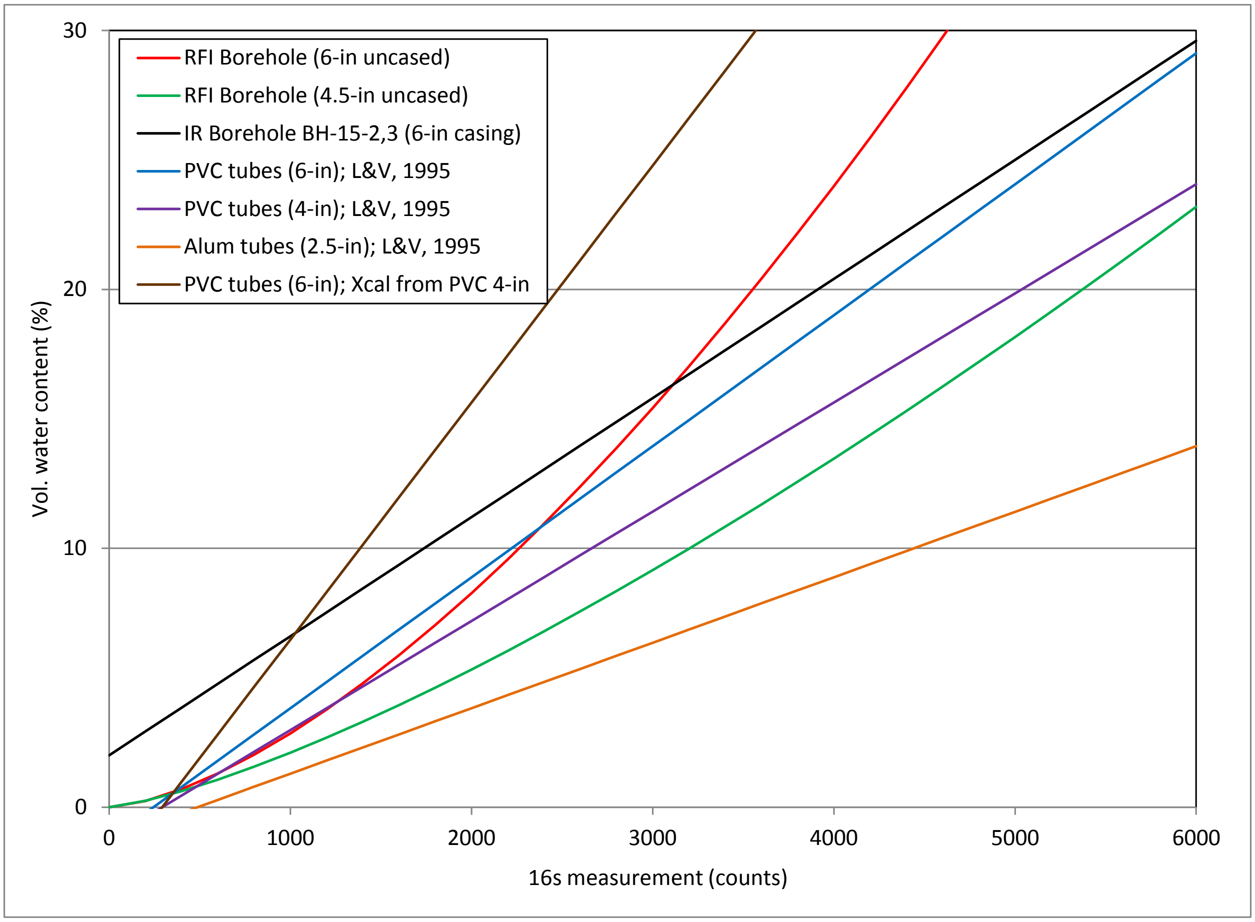


Figure 39. Comparison of all neutron probe calibration used at Area G. Calibrations that use a count ratio were converted to 16s counts by dividing by an assumed standard count of 6900.

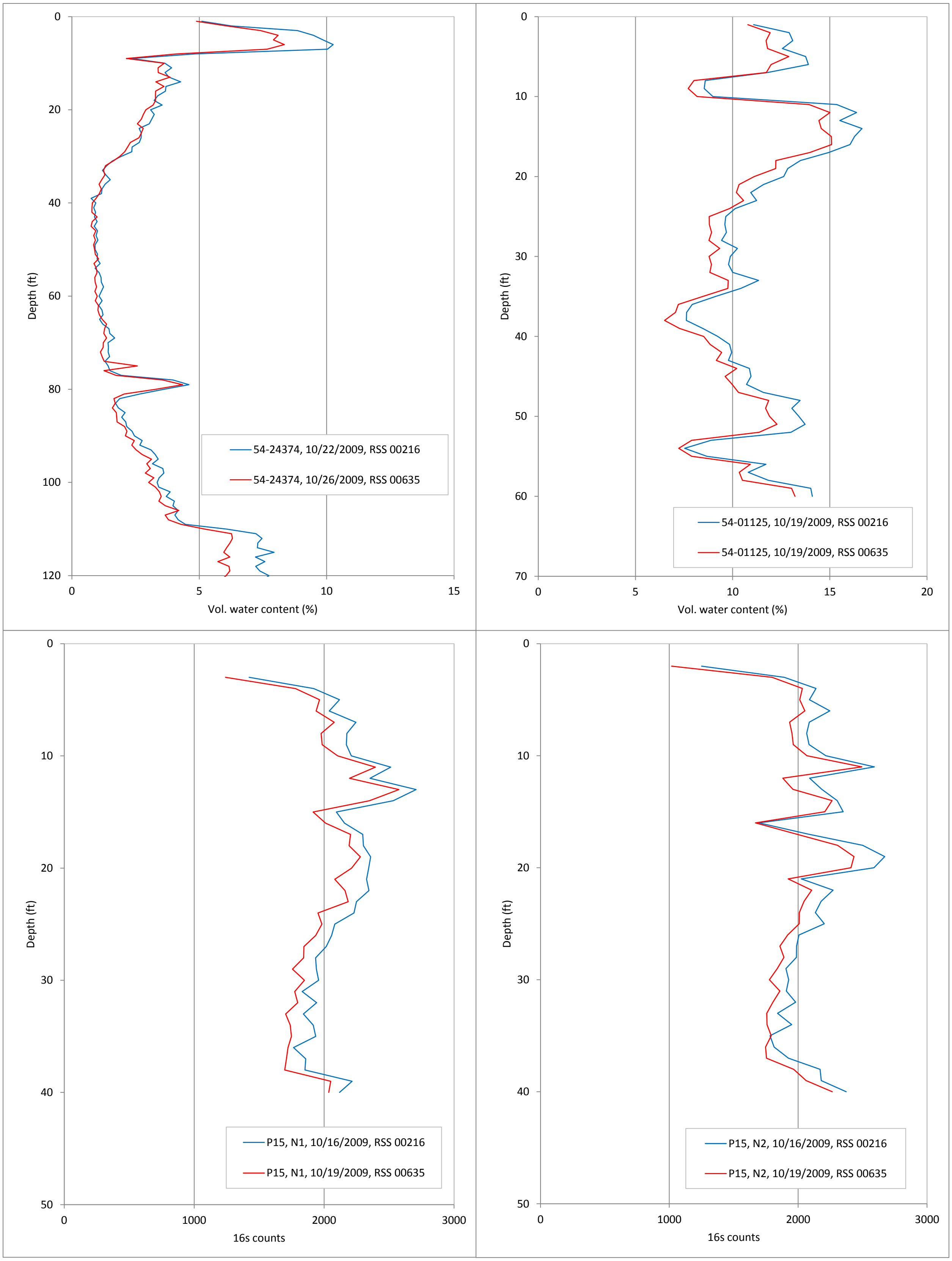


Figure 40. Comparison of two neutron probes in boreholes and access tubes.

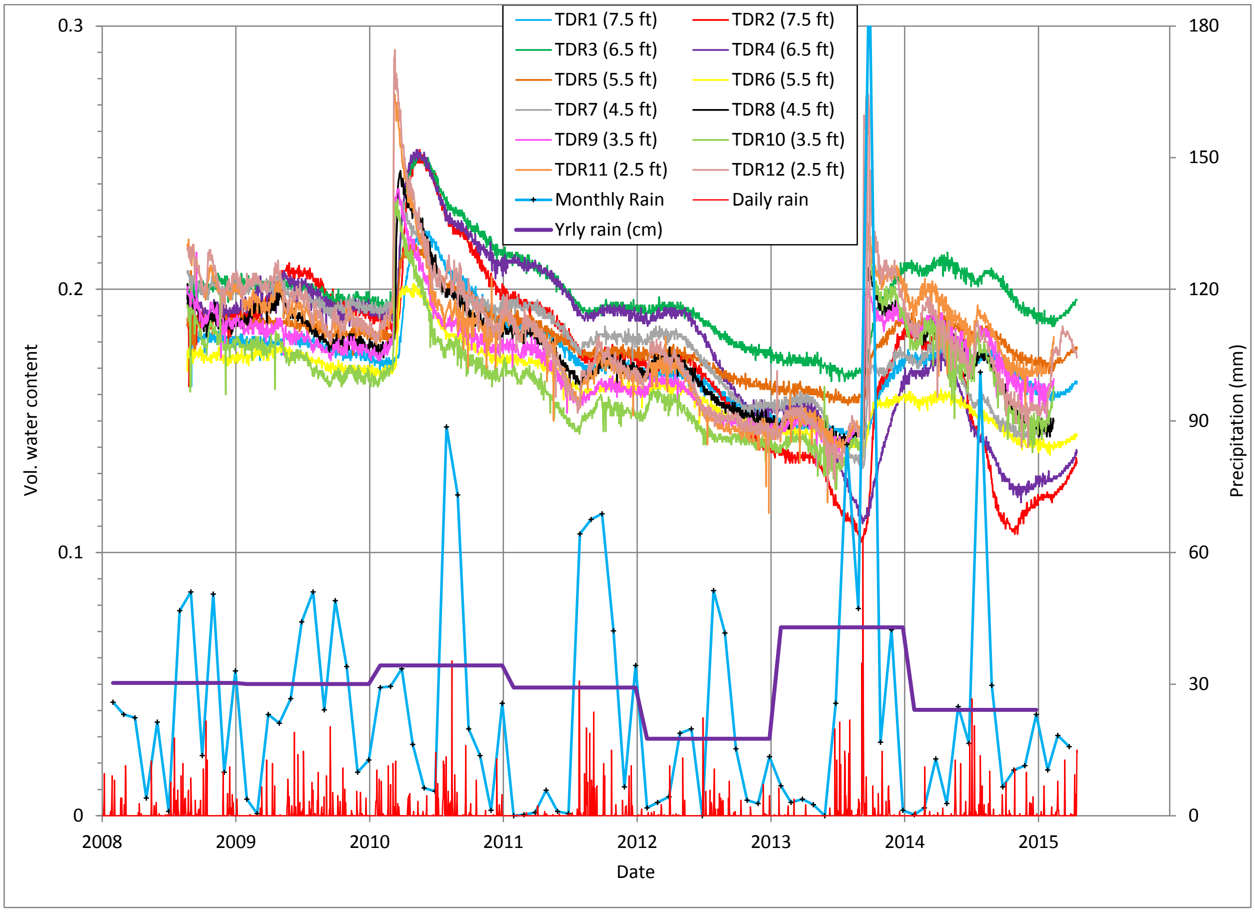


Figure 41. Time series of water content measured in the ET cover at Pit 31.

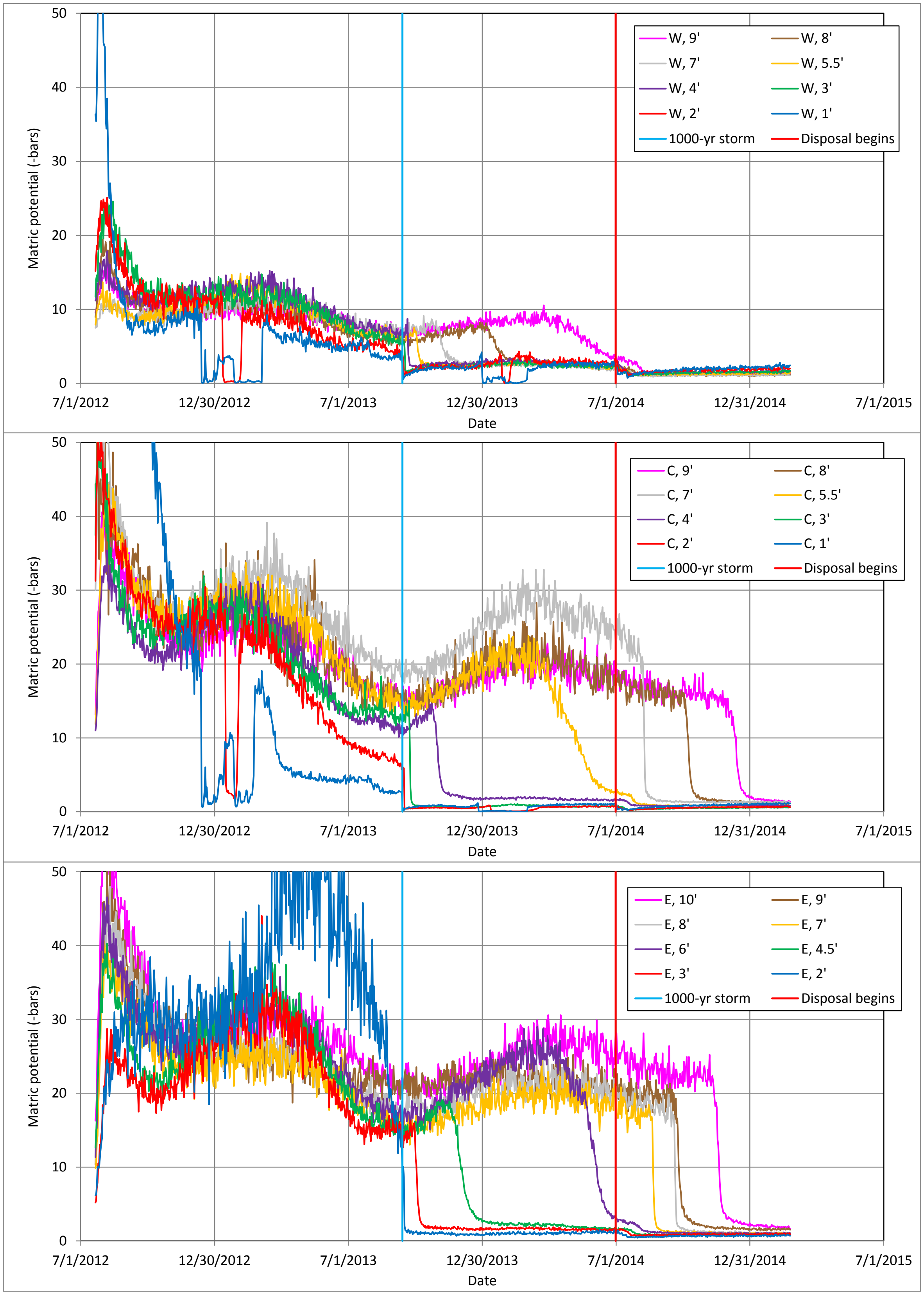


Figure 42. Times series of matric potential measured beneath the P38X floor.

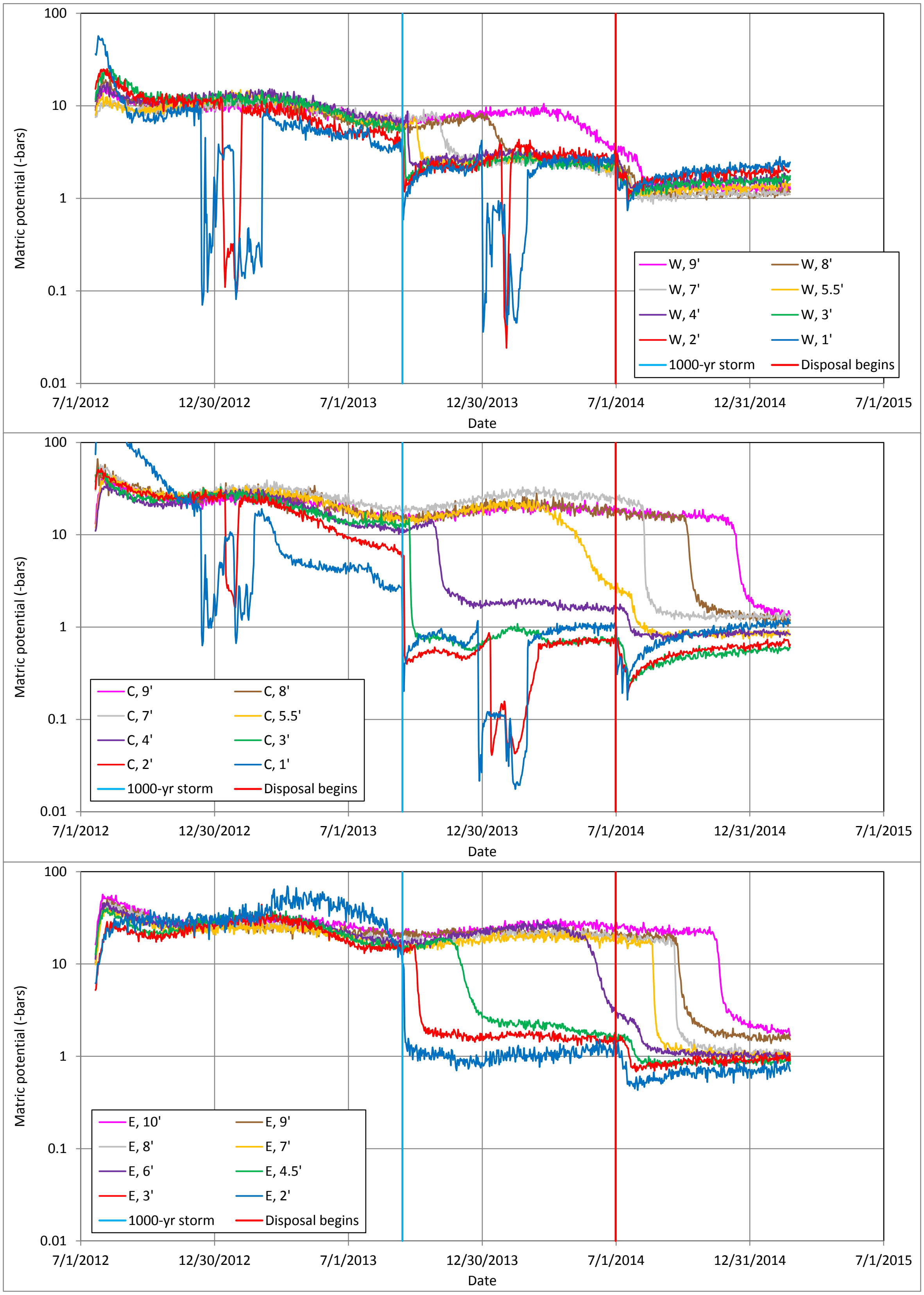


Figure 43. Times series of matric potential measured beneath the P38X floor with y-axis log scale.

Figure 44. Photo showing floor of Pit38-Ext on Sept. 19, 2013 (facing west).

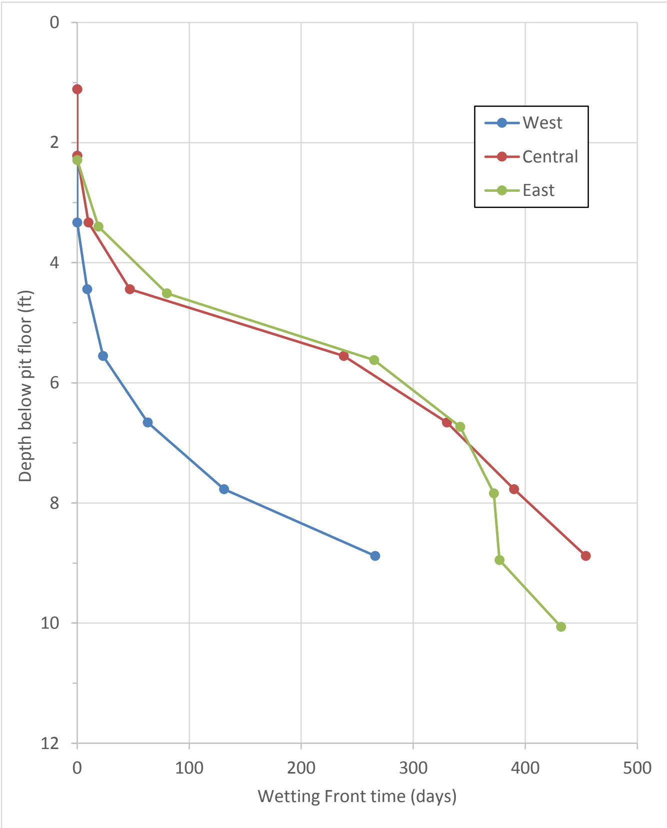


Figure 45. Time for wetting front to reach sensors beneath P38X following 1,000-yr storm of 2013.

Appendix A. Data Sources

Neutron logging data acquired for the preparation of this report came from 3 primary sources: 1) the Project repository from Northwind Inc. (former subcontractor); 2) data files for the Medusa boreholes from Steve McLin (retired LANL employee); and 3) data files maintained by Dennis Newell (former LANL employee). The neutron logging data collected in 2013 by Portage (subcontractor) was provided to the authors in the form of pdf files.

All original data from Northwind, Steve McLin, and Dennis Newell are preserved in their original file structure and new data analysis is included in other folders. This file structure is shown below. The check marks are generated by the Subversion software (http://svnbook.red-bean.com/) that is used by Neptune and Co. Inc., as a data backup system. All neutron logging data reside on Neptune's Subversion backup. In addition, the file structure shown below accompanies submission of this report to LANL.