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Environmental Sciences Laboratory

Applied Studies & Technology Variation in Groundwater Aquifers: Results of Phase II Field Investigations and Final Summary Report

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U.S. DEPARTMENT OF ENERGY | Legacy Management

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Abbreviations

AL	alluvium
AS&T	Applied Studies and Technology
BDL	below detection limit
bgs	below ground surface
Ca	calcium
CBE	charge-balance error
CFR	*Code of Federal Regulations*
CI	confidence interval
Cl	chloride
CV	coefficient of variation
DOC	dissolved organic carbon
DOE	U.S. Department of Energy
Fe	iron
ft	feet
ft/d	feet per day
ft/ft	feet per feet
GEMS	Geospatial Environmental Mapping System
gpm	gallons per minute
ICP-OES	inductively coupled plasma–optical emission spectrometry
K	potassium
KM	Mancos Shale (also Km)
LM	Office of Legacy Management
Mg	magnesium
mg/L	milligrams per liter
µm	micron
µS/cm	microsiemens per centimeter
mL	milliliters
mL/min	milliliters per minute
Na	sodium
NO_3	nitrate
pCi/L	picocuries per liter
r	correlation coefficient (Pearson's r)
r^2	r squared, coefficient of determination

redox	oxidation-reduction (reaction)
^{222}Rn	radon-222
SC	specific conductance
SCT	specific conductance and temperature (profiling)
SOARS	System Operation and Analysis at Remote Sites
TDS	total dissolved solids
TOC	total organic carbon
UMTRCA	Uranium Mill Tailings Radiation Control Act

Executive Summary

This report documents the results of Phase II of the Applied Studies and Technology (AS&T) project titled *Variation in Groundwater Aquifers*, herein referred to as the "Variation Project." The catalyst for this study was the observation in 2012–2013 that concentrations of dissolved ions and selected contaminants varied with depth in groundwater monitoring wells at several former uranium-ore processing and disposal sites managed by the U.S. Department of Energy Office of Legacy Management (LM). In some cases, the range in specific conductance (an indicator of dissolved ion concentrations), uranium, and other contaminants measured over a decade or more in a well could be reproduced in several hours by sampling the well at different depths. Based on these data, LM undertook an investigation to assess the extent of vertical chemical stratification that occurs in monitoring wells at sites managed under the Uranium Mill Tailings Radiation Control Act (UMTRCA) program.

This study entailed two phases. Phase I was conducted to assess the overall prevalence of vertical stratification in LM site monitoring wells based on measurements of specific conductance (SC), a measure of salinity, alone. Between July 2013 and October 2014, SC and temperature profiles were obtained at 0.5-foot (ft) intervals in 400 monitoring wells at 15 LM sites in the western United States. At all sites profiled, underlying groundwater contains elevated concentrations of milling-related constituents, primarily uranium. This profiling effort culminated in the submittal of the 2015 AS&T report titled *Variation in Groundwater Aquifers: Results of 2013–2014 Phase I Field Investigations*.

Most (about 70%) of the wells profiled in Phase I had little variation in the SC profiles—that is, SC measurements were fairly consistent within the saturated portion of the monitoring well. This was not the case, however, at two LM sites located on river floodplains—the Durango, Colorado, Processing Site and the floodplain portion of the Shiprock, New Mexico, Disposal Site. At these sites, dissolved ion concentrations (as indicated by SC) increased with depth, at times markedly, and, in many cases, within the screened interval of the monitoring wells. Review of historical monitoring data indicated that this stratification in SC might correlate with site contaminants or other parameters. For these reasons, these two floodplain sites were selected for further evaluation in Phase II.

Phase II focused on investigating whether the measured vertical variation in SC corresponds to similar variation in milling-related constituents—in particular, uranium. The scope of this phase of the study was designed to help answer the following three primary questions:

- First, do measured values of SC in a monitoring well co-vary with uranium or other milling-related constituents?
- Second, if the answer to the first question is "yes," can SC be used as an indicator of uranium concentrations or other site contaminants in groundwater?
- Third and finally, how might the results of this study improve LM's groundwater monitoring strategies at these and other UMTRCA sites?

The answers to these questions were sought in field investigations conducted between August and November 2015, when vertical profiles of SC and selected constituents were obtained at 24 wells at the Durango processing site and 36 wells on the Shiprock site floodplain.

At each well, following initial SC profiling, groundwater samples were collected at 1 ft vertical intervals and analyzed for uranium, major ions (including sulfate), nitrate, organic carbon, iron, and pH. Vertical profiles of radon-222 (^{222}Rn), a direct indicator of groundwater residence time in a monitoring well, were also obtained in a subset of the wells. Samples were analyzed at the LM Environmental Sciences Laboratory in Grand Junction, Colorado. To verify well construction information, especially screen placement, downhole video camera surveys of Durango and Shiprock site wells were conducted in the spring and summer of 2016.

One of the major findings of this study was that the analytical results for a given well, particularly at floodplain sites, can vary markedly depending on the depth at which samples are collected, even within the screened interval of the well. This was found for uranium, sulfate, and other constituents at both the Durango and Shiprock sites.

The first goal of this study was to determine the degree of correlation between SC and milling-related constituents (e.g., uranium), if any. Based on chemical profiling at the Durango processing site, there is no apparent correlation between SC and uranium, the primary indicator of milling-related contamination. Although concentrations of dissolved ions and uranium did vary in many of the wells profiled, no consistent pattern was observed. In fact, in the majority of the wells, uranium decreased with depth, in contrast to the increasing trend observed for SC. Overall, chemical profiles in Durango processing site wells were inconsistent and varied within the interwell network. This might be due to the complex geology at the site, which consists of two hydrogeologically separate areas. Five distinct geologic formations are represented within the monitoring well network, and many of the wells profiled are screened in two strata.

Unlike the Durango processing site, many of the wells profiled on the floodplain portion of the Shiprock site had a strong correlation between SC and uranium (and other analytes), in particular those with the highest degrees of variation measured in Phase I. Analysis of historical monitoring data (pairwise comparisons of SC vs. uranium) yielded similar conclusions. With regard to the second goal of this study, these findings support using SC, an easily obtained measure of salinity, as a cost-effective surrogate for monitoring uranium and sulfate in wells where this correlation has been established.

The third question driving this investigation was to assess whether the observed intrawell variation could improve LM's groundwater monitoring strategies at selected sites. A related goal is to better understand groundwater contaminant behavior and spatial distributions and to improve interpretations of sampling data. The results of this study highlight the importance of:

(1) sampling groundwater monitoring wells at consistent depths, a prerequisite for valid trend analysis of the data, especially if chemical stratification has been measured (as feasible, accounting for seasonal water level fluctuations);

(2) recording sample depths routinely (where the "*z*" elevation component is equally important as the "*x*" and "*y*" spatial variables); and

(3) periodically verifying that those depths correspond to the representative portion of the aquifer being monitored.

LM follows well-established protocols for groundwater sampling and laboratory analysis, in accordance with industry-accepted procedures (e.g., those developed by ASTM International or the U.S. Environmental Protection Agency). In following these protocols, there was an inherent assumption that the water quality within the screened interval of a monitoring well was relatively homogenous and, therefore, a representative sample could be obtained from any depth within that interval. As a result, sample depths were not recorded routinely, and they may not have been consistent. At some LM site alluvial wells, depending on the groundwater elevation, it is likely that samples were often collected from the lower screen or even the sump portion of a well.

If, as was found in this study, dissolved ion and contaminant concentrations vary with depth in some LM site monitoring wells, this could affect interpretations of corresponding temporal trends, especially when using low-flow sampling techniques. These findings underscore the importance of maintaining consistent depths when sampling and routinely documenting those depths (as a data point or record) at LM sites. Since this study was initiated in 2013, LM has modified its sampling protocols accordingly, requiring fixed sample intake depths and routine documentation of those elevations.

Results of this study also highlight the importance of considering well construction (screen placement) and understanding groundwater flux patterns when developing or refining monitoring strategies. For example, at the Durango processing site, the observed variation in both SC and uranium profiles is likely attributed to the fact that many wells are screened in two formations, a factor that can introduce uncertainty into the sampling results and data interpretations.

Other conditions potentially accounting for the variation found in SC and chemical profiles in the wells profiled in this study include density-driven flow (which could account for salinity increasing with depth), preferential flow paths (including fracture flow); and stagnant zones in wells, as indicated in several ^{222}Rn profiles. Although the extent to which these factors account for the observed vertical variation is beyond the scope of this study, awareness of these potential mechanisms is important when evaluating groundwater behavior at LM sites. This study confirmed that ^{222}Rn profiles in monitoring wells are useful for discerning between zones with high groundwater influx and zones that are relatively stagnant. The latter, coupled with periodic downhole video profiling (to confirm screen placement and assess well integrity), could help refine groundwater sampling regimes at existing or newly transitioned LM sites.

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1.0 Introduction

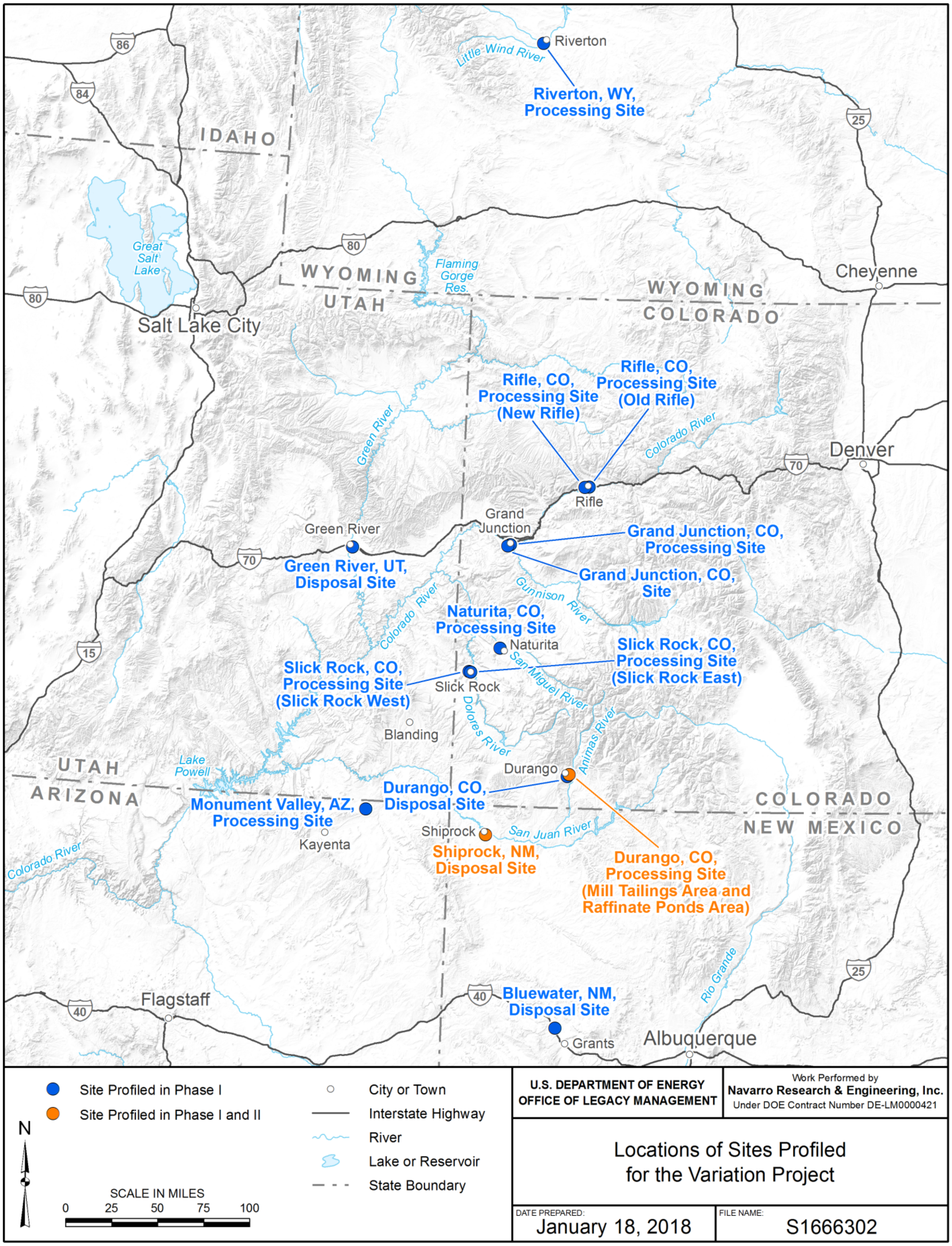
This report documents the results of Phase II of the Applied Studies and Technology (AS&T) project V*ariation in Groundwater Aquifers,* herein referred to as the "Variation Project." The catalyst for this study was the observation in 2012–2013 that dissolved ion and contaminant concentrations varied with depth in groundwater monitoring wells at several former uranium-ore processing and disposal sites managed by the U.S. Department of Energy (DOE) Office of Legacy Management (LM). In some cases, the range in specific conductance (SC), an indicator of dissolved ion concentrations, measured over a decade or more in a well could be reproduced in a few hours by sampling the well at different depths. This same vertical stratification (changes in concentrations with depth) also applied to uranium and other site-related constituents. Based on these findings, LM undertook an investigation to assess the extent of vertical chemical stratification that occurs in monitoring wells at sites managed under the Uranium Mill Tailings Radiation Control Act (UMTRCA) program.

The Variation Project study plan entailed two phases. Phase I was conducted to assess the overall prevalence of vertical chemical stratification in LM site monitoring wells based solely on the variation in SC, an indicator of salinity, alone. Phase II, the focus of this report, investigated whether the vertical variation in SC correlated with corresponding concentrations of site contaminants, in particular, uranium.

The Phase I effort, documented in the 2015 AS&T report titled *Variation in Groundwater Aquifers: Results of 2013–2014 Phase I Field Investigations* (DOE 2015), focused only on the relationship between SC and depth. The goal of that effort was to establish a baseline of SC profiles at 15 LM sites in the western United States (Figure 1). At all sites profiled, underlying groundwater contains milling-related constituents, primarily uranium. Between July 2013 and October 2014, SC and temperature profiles were obtained at 0.5 to 1 foot (ft) intervals in 400 monitoring wells.

Most of the wells profiled (about 70%) had little variation in the SC profiles. This was not the case, however, at two LM sites located on river floodplains: the Durango, Colorado, Processing Site and the floodplain portion of the Shiprock, New Mexico, Disposal Site (Shiprock site). At these sites, SC profiles indicated strong vertical chemical concentration gradients in the groundwater monitoring wells. Based on comparisons with historical monitoring results, there were also some indications that the stratification in SC might correlate with milling-related constituents (e.g., uranium) or other parameters. For these reasons, the Durango and Shiprock sites were selected for further evaluation in Phase II.

Three primary study questions determined the scope of the Phase II effort. First, does the observed vertical variation in SC apply to other parameters—that is, does SC co-vary (correlate) with uranium or other milling-related site constituents? Second, if the answer to the first question is "yes," can SC be used as a surrogate or indicator of uranium or other site contaminants in groundwater? Third and finally, how might the results of this study improve LM's groundwater monitoring strategies at these and other UMTRCA sites? The answers to those questions were sought in field investigations conducted between August and November 2015, when vertical profiles of SC and chemical parameters were obtained at 24 wells at the Durango processing site and 36 wells on the Shiprock site floodplain.



Note: For purposes of this study, each geographically and hydrogeologically distinct area of an LM site is treated as a separate study area or "site." This approach differs somewhat from the counting approach applied in LM's Site Management Guide (DOE 2017), whereby sites in a given locale or region (e.g., Durango, Colorado) are treated as one site.

Figure 1. Locations of LM Sites Profiled for the Variation Project

At each well, following initial SC profiling, samples were collected at 1 ft vertical intervals using low-flow sampling techniques and analyzed for uranium, major cations and anions (including sulfate), nitrate (as NO_3), organic carbon, iron, pH, and (for a subset of wells) radon-222 (^{222}Rn). This effort yielded nearly 700 samples (15 to 16 analytes per sample) that were used to assess correlations between SC and uranium, as well as the remaining possible 119 variable combinations.

1.1 Study Area Descriptions

The Durango and Shiprock sites are 2 of 22 inactive uranium ore-processing sites managed by LM under the UMTRCA Title I program. Although these two sites differ in their respective milling history and compliance strategies, groundwater underlying both sites contains elevated levels of constituents related to the former processing activities, most notably uranium. LM performs routine water quality monitoring annually (usually in June) at the Durango site and semiannually (March and September) at the Shiprock site.[1]

Located about 0.25 mile southwest of the central business district of Durango, Colorado, the Durango processing site consists of two separate areas: the mill tailings area, which includes the former uranium-ore milling and storage of mill tailings; and the raffinate ponds area, where liquid process wastes were impounded during milling operations. Because these areas are hydrologically and geologically distinct, they are treated separately in this report. Both areas of the site are adjacent to the Animas River.

The Shiprock disposal site is located near the town of Shiprock in northwestern New Mexico. The former mill was built on a terrace of Mancos Shale that rises about 60 ft above a floodplain of the San Juan River, which bounds the floodplain to the north and east. The site is divided into two distinct areas that are separated by an escarpment: the terrace and the floodplain. The disposal cell is located on the terrace portion of the site where only limited profiling took place in Phase I of this study. This study focuses only on the floodplain portion of the site adjacent to the San Juan River, where a pump-and-evaporate system has been in place to enhance groundwater cleanup since 2003.

1.2 Background

In accordance with Goal 1 of LM's *2016–2025 Strategic Plan* (DOE 2016a)—*protection of human health and the environment*—two objectives of LM's long-term surveillance and monitoring approach at its sites are to (1) reduce postclosure-related health risks in a cost-effective manner and (2) improve the long-term sustainability of environmental remedies. Consistent with these objectives, a major goal at many sites is to understand groundwater contaminant behavior and corresponding spatial distributions. These interpretations are based, in part, on groundwater monitoring data—samples collected routinely (typically annually or semiannually) in monitoring wells, usually at single (e.g., mid-screen) depths. These data are used to characterize the existing groundwater conditions and assess historical changes and are also used (in part) as the basis for estimating future trends and conditions.

[1] Corresponding groundwater quality standards are those in Title 40 *Code of Federal Regulations* Section 192 (40 CFR 192).

Figure 2 shows a simplified schematic of a groundwater monitoring well that includes the well screen and casing and a hypothetical contaminant vertical profile. The water column thickness in an alluvial well is a function of the water table elevation with respect to the bottom of the well. Although preferably obtained within the screened interval (which, in this study, ranged from 2 to 40 ft in length), samples could be collected from anywhere in the water column. The example shown in Figure 2 is typical of many of the wells profiled in this study in that SC and contaminant levels vary (typically increase) with depth, even within the screened interval. In these cases, if samples are collected at single (often unrecorded) depths, how does this affect interpretations of the data for reporting or modeling purposes?

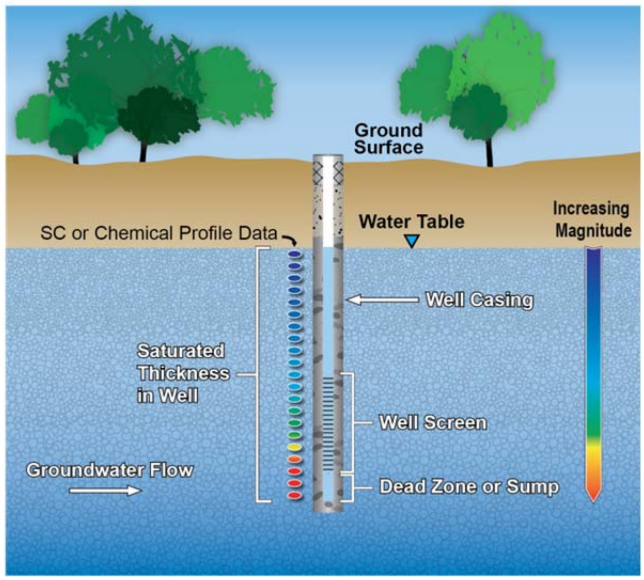
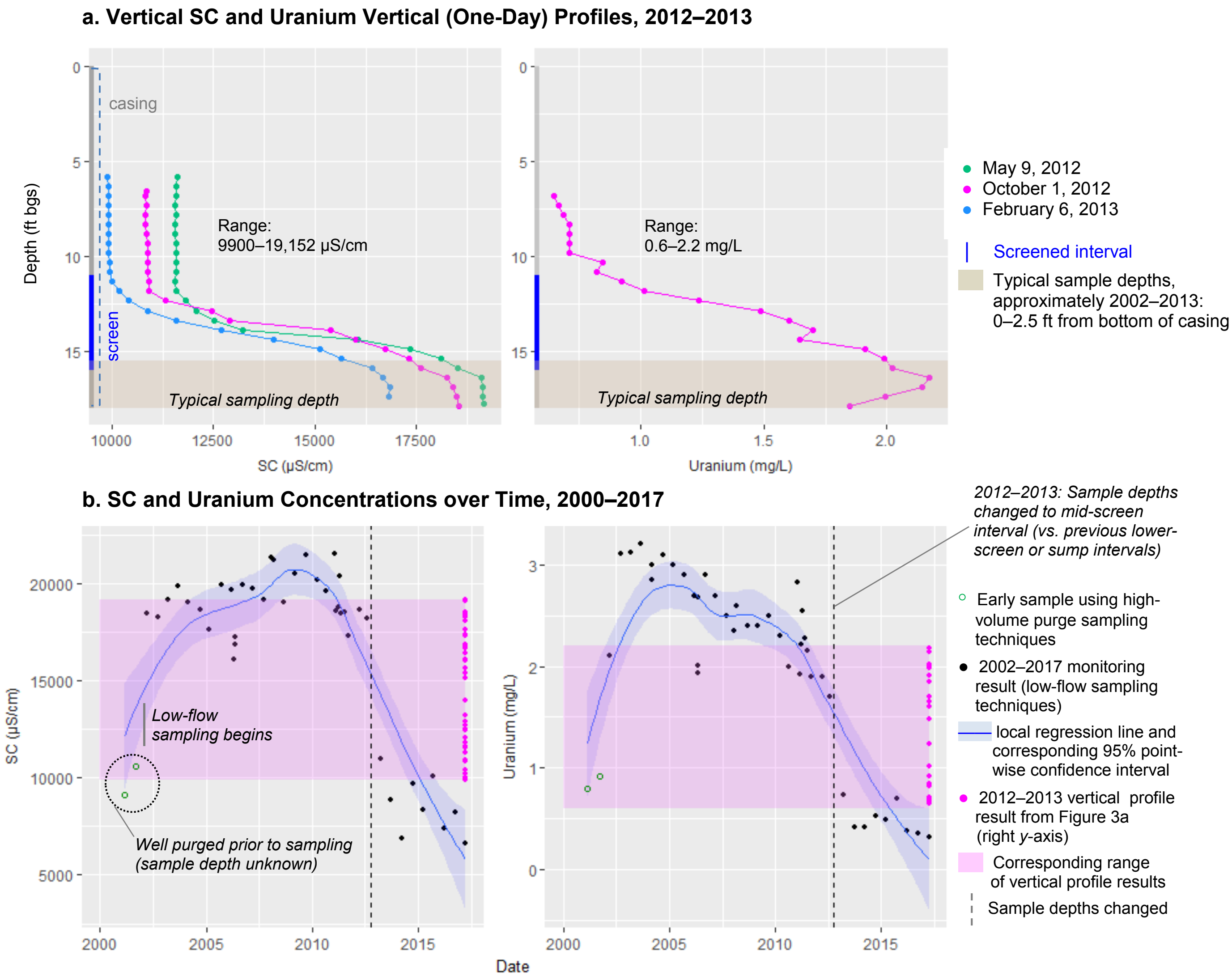


Figure 2. Simplified Schematic of a Groundwater Monitoring Well with Example Contaminant Profile

LM follows the sampling and analytical protocols found in the *Sampling and Analysis Plan for U.S. Department of Energy Office of Legacy Management Sites* (LMS/PRO/S04351). These protocols, developed based on ASTM International procedures or sampling methods recommended by the U.S. Environmental Protection Agency, are continually updated to reflect any new guidance. In following these protocols, there was an inherent assumption that the groundwater quality within the screened interval of a monitoring well was relatively homogenous and, therefore, a representative sample could be obtained from any depth within that interval. Work conducted on the Shiprock site floodplain in 2012–2013, a precursor to this study, revealed that this assumption did not hold true for some wells. Rather, this early profiling indicated that both SC and uranium concentrations in samples collected from several wells varied with depth, even within the screened interval.

Shiprock site well 0618 is completed in the alluvium in the central portion of the uranium plume. As shown in Figure 3a, SC varied in this well by as much as 8000 microsiemens per centimeter (µS/cm) over a vertical span of about 10 ft. Within that same interval, uranium concentrations more than tripled with increasing depth, from 0.6 to 2.2 milligrams per liter (mg/L). The bulk of the change in both SC and uranium concentrations occurred within the 5 ft screened interval, 9–16 ft below ground surface (bgs). The most likely sampling interval at that time, the bottom 2–2.5 ft of the well (15.5–18 ft bgs), is shaded in the figure.



Notes:
Plot (a) shows SC and uranium measured vertically in well in 1 day; three distinct SC profiles were taken in 2012–2013. SC nearly doubles and uranium more than triples within the profiles. Magnitudes also change within the screened interval. Plot (b) shows SC and uranium measured over time (2000–2017) in the same well. The pink-shaded region denotes the range of SC and uranium measured in 1 day (from plot a). The vertical variation found in one day is as large as the variation measured over a decade.

Figure 3. Initial Catalyst for the Variation Project, Shiprock Site Floodplain Well 0618

Acknowledging the potential for stratification in some wells and the resulting importance of sampling at consistent depths, in about 2013, sample depths in Shiprock site wells were changed to mid-screen intervals. The marked decrease in SC and uranium concentrations between 2012 and 2013 (Figure 3b) could result from changing flow patterns associated with remediation pumping or other processes in this region of the floodplain (DOE 2016c). However, given the vertical stratification shown in Figure 3a, the attenuation could also reflect the change in sample depths. Although not the focus of this report, Figure 3b also illustrates the potential effects of changing from high-flow purge methods (used before 2002) to “low-flow” sampling methods (DOE 2016c). Another observation stemming from this figure is the appearance of a strong correlation between SC and uranium. This is evident in both the vertical profiles (Figure 3a), as well as the plot of historical results (Figure 3b).

If the intrawell variation in constituent concentrations shown in the previous example applies to other LM site wells, the question arises, "how can this new knowledge enhance the effectiveness of LM's long-term surveillance and monitoring operations?" For example, the understanding that contaminant concentrations may vary within a well highlights the importance of recording sample depths, especially when using low-flow sampling methods. Rather than assuming a uniform (single) concentration, accounting for potential subsurface variation could refine assessments of plume mass, site remediation progress, and chemical concentration trends.

If SC correlates with uranium or other contaminants as shown in the preceding example, then its potential for use as a cost-effective surrogate or monitoring tool warrants consideration. Consistent with the real-time data collection methods that are the cornerstone of LM's System Operation and Analysis at Remote Sites (SOARS) program (DOE 2018b), use of SC as a surrogate could support reducing the number of locations to be sampled for chemical analysis and improve understanding of transient contaminant behavior. The goal of this report is to use the Phase II field and laboratory results to (1) answer the questions raised above and (2) provide information that furthers LM's understanding of groundwater systems and associated monitoring strategies at its sites.

1.3 Organization of this Report

Following this introduction, Section 2 provides an overview of the results of the 2013–2014 field effort, documented in detail in the Phase I report (DOE 2015). Section 3 summarizes the field and laboratory methods used in this study, as well as the technical approach used to assess SC and contaminant profiles. Sections 4 and 5 document the Phase II results for the Durango processing site and the floodplain portion of the Shiprock site, respectively. Discussions of the results are presented in Section 6; Section 7 summarizes the major findings of the Phase II investigation. References are provided in Section 8.

Appendix A provides a graphical summary of Phase I SC profile results for the 12 sites profiled only in Phase I and not evaluated in this report.[2] For each of these sites, this appendix also includes a brief synopsis of results identifying the wells with the most variable SC profiles. Appendix B elaborates upon the study methods discussed in Section 2, summarizing field observations made during sample collection and observations made during downhole video profiles of wells, taken between April and August 2016.

Phase II entailed the collection of nearly 700 samples at 60 wells for 15 to 16 analytes, yielding roughly 960 well-variable combinations. Appendixes C–E provide a graphical summary of all profile data obtained for each site profiled in Phase II, first by variable, and then by well.

Appendix F includes an LM white paper prepared in September 2013, "Specific Conductivity and Chemical Profiles of Shiprock Floodplain Wells 0857 and 1136–1139: July 2013." The work described in this paper fed directly into the work for this study and serves as a baseline of chemical profiles for some wells located near the San Juan River on the Shiprock site floodplain.

[2] For purposes of this study, each geographically and hydrogeologically distinct area of an LM site is treated as a separate study area or "site." This approach differs somewhat from the counting approach applied in LM's Site Management Guide (SMG) (DOE 2017), whereby sites in a given locale or region are treated as one site. For example, the three distinct areas of the Durango, Colorado, Disposal/Processing site—the two processing areas and the disposal cell 3.5 miles southwest of Durango—are treated as one site in the SMG, but not in this report.

2.0 Summary of Phase I Variation Project Findings

The purpose of Phase I of the Variation Project was to assess whether the high degree of stratification in SC observed in several Shiprock site floodplain wells was unique to that site or if it was occurring at other LM sites and wells. To investigate this question, between July 2013 and October 2014, SC and temperature profiles were obtained from 400 monitoring wells at the 15 LM sites shown in Figure 1. Results of this investigation were documented in the Phase I report (DOE 2015). This section outlines the approach used to interpret the large data set yielded from that effort (nearly 17,500 SC measurements) and summarizes the most salient findings.

2.1 Indices of Variation

To provide a context for evaluating the Phase I results, it was necessary to derive an index of variation so that SC profiles (or the degree of variation) could be compared within and between sites. Although several statistical approaches were considered for categorizing these results, the coefficient of variation (CV)—the ratio of the standard deviation to the mean and a commonly applied measure of dispersion—was ultimately selected. Because it is a unitless statistical parameter (and therefore not influenced by the magnitude of measurements), it allows comparison of data between wells.

As documented in the Phase I report (DOE 2015), three categories of variation were defined: low ($CV < 0.03$), mid-level ($0.03 \leq CV < 0.1$), and high ($CV \geq 0.1$). To illustrate how these categories might be applied, Figure 4 shows a subset of Phase I SC profile results obtained from three wells at the Bluewater, New Mexico, Disposal site in October 2014.

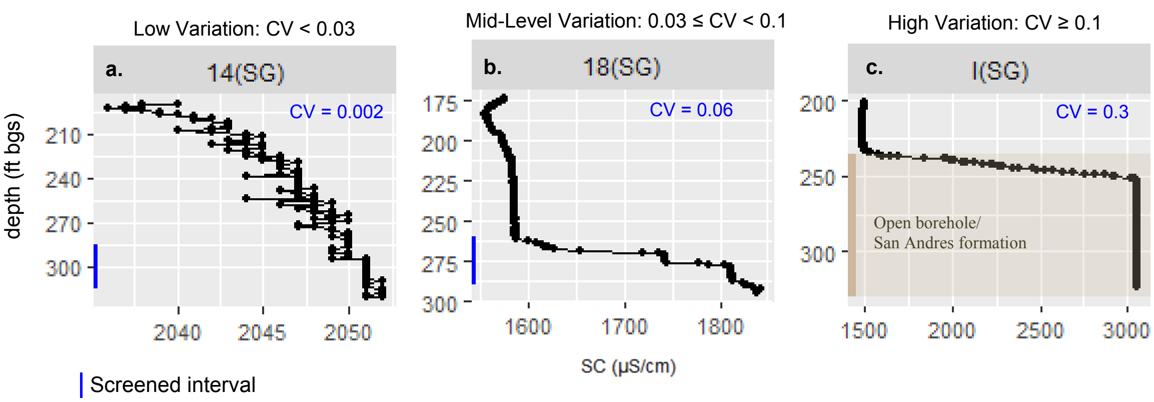
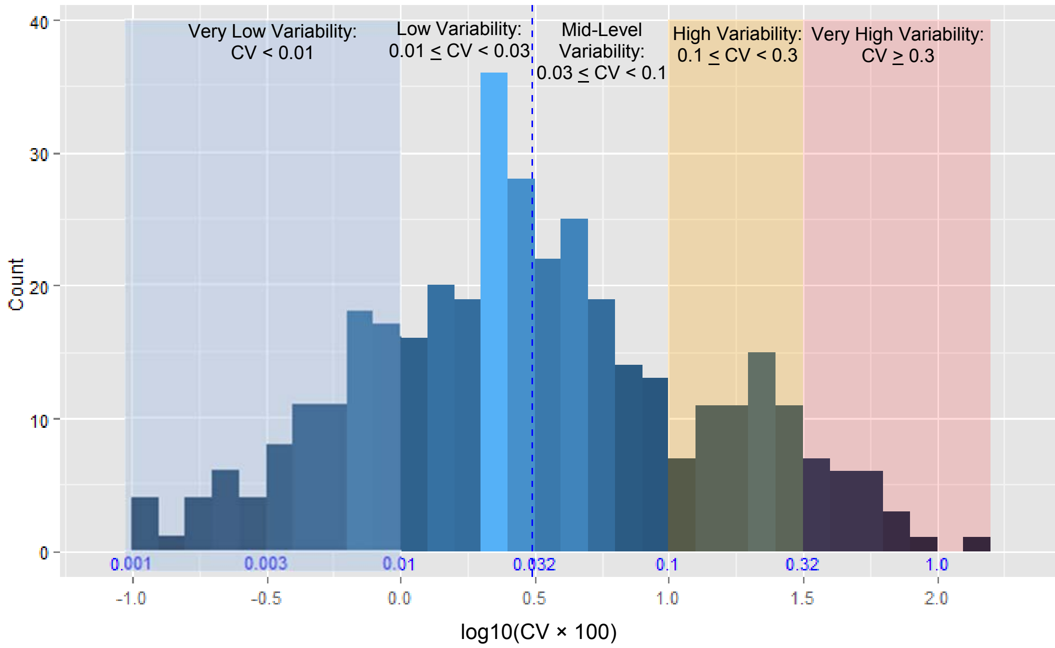


Figure 4. Subset of Specific Conductance Profiles from the Phase I Report, from the Bluewater, New Mexico, Disposal Site: Examples of (a) low variation, (b) mid-level variation, and (c) high variation.

An example of very small changes in SC with depth is shown in Figure 4a, the SC profile obtained from the Bluewater site well 14(SG). Over a span of about 130 ft, SC varied by just 16 µS/cm, yielding a CV of 0.002. Although SC clearly varies in this well (there is a slight increase with depth), this variation is probably not meaningful, but instead may be an example of random variation. The profiles are different for wells 18(SG) and I(SG), examples of mid-level and high variation categories, respectively. In well 18(SG), SC increased by about 300 µS/cm at the onset of the screened interval. In well I(SG), SC more than doubled at the transition from the upper casing to the open borehole San Andres formation.

2.2 Phase I Study Findings

Using the categories defined above, most wells profiled in Phase I (about 70%), had low to mid-level variation (Figure 5). In this histogram, the low and high variation categories are further subdivided (or binned based on the CV) consistent with the approach used in the Phase I report.



Notes:
Adapted from Figure 9 of the Phase I report (DOE 2015) based on SC profiles in 375 LM site wells. Numbers appearing in blue on the *x*-axis denote the equivalent non-transformed CV value. The vertical blue dashed line denotes the cutoff between low (CV < 0.03) and mid- to high-level variation.

Figure 5. Distribution of CVs and Cutoffs for Defining Ranges of Variability Used in the Phase I Report

Figure 6 shows the corresponding site-specific distributions, ranked by the median CV. In Figure 6, each box represents the overall distribution of CVs at each site, and each point represents an individual well and the corresponding CV. While the Shiprock site floodplain and both areas of the Durango processing site have high-level variation in SC profiles in most wells, other sites have overall very little variation (Figure 6). At all sites, several wells showed some vertical stratification and every site has at least one well with a highly variable SC profile (CV ≥ 0.1). This variation should be acknowledged when interpreting historical monitoring results, particularly for those wells where there is an apparent correlation between SC and site contaminants. For example, the increase in SC measured in Bluewater site point of exposure well I(SG), corresponding to the transition from the upper well casing to the San Andres formation (Figure 4c), was also found for uranium. This finding was important to LM's interpretation of groundwater contaminant trends and plume movement at that site (Section 7.2.1.2 in DOE 2014b; Figure 14 in DOE 2015).

The Phase I profile results indicate highly varying SC profiles at many of the wells profiled at the Durango processing site (both mill tailings and raffinate ponds areas) and the floodplain portion of the Shiprock site. Based on these findings and the relative ranks illustrated in Figure 6, these sites were selected for further evaluation in Phase II. A major focus of Phase II was to determine whether the same degree of variation in SC found vertically would be true for site contaminants or other constituents.

Notes:
Adapted from Figure 75 of the Phase I report (DOE 2015). The uppermost box and jitter plot duplicates the summary plot provided in Section 3 of that report, where each point represents an individual well. The lower "violin" plot shows the same data in a slightly different format, illustrating the probability density of the data at different values. For sites where the majority of wells had low- to mid-level variation in the SC profiles, this density appears as a baglike shape in the left portion of the plot.

Figure 6. Box and Violin Plots of Phase I SC Profile Data, Ranked by the Median CV

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3.0 Phase II Methods

SC and chemical profiling was conducted at the Durango processing site in August–September 2015. The bulk of the work was conducted August 24–28, 2015; remaining work including ^{222}Rn profiling was completed September 21–24, 2015. Because of the relatively small number of wells within the two site areas, all wells were chosen for profiling, including the four background wells at the former mill tailings area. Downhole camera surveys of the wells were conducted in July 2016.

Well profiling and sampling was conducted at the floodplain portion of the Shiprock site October 19–29, 2015. Because of the large number of existing wells on the floodplain (98, 85 of which were profiled in Phase I of the study), only a subset (36) was selected for chemical sampling in Phase II. A proportion of low and mid-level variability wells was included in this subset to test the hypothesis that little to no variation in SC implies a corresponding lack of variation in contaminant profiles. Downhole camera surveys of the profiled floodplain wells were conducted in April 2016.

Table 1 summarizes the Phase II field effort at the Durango and Shiprock sites. Appendix B expands upon the summary material presented in this section, summarizing field observations made during Phase II profiling and sample collection, as well as screen depth measurement and observations during the downhole camera surveys.

Table 1. Summary of Phase II Field Effort

LM Site	Dates Profiled[a]	Number of Wells Profiled	Number of SC Measurements	Number of Samples for Chemical Analysis[b]	Number of Wells Profiled for ^{222}Rn
Durango processing site mill tailings area	August–September 2015	13	260	104	8 (52 samples)
Durango processing site raffinate ponds area	June 2015	11	706	262	3 (54 samples)
Shiprock site floodplain	October 2015	36	655	325	10 (123 samples)
	Total:	60	1621	691	229

Notes:
[a] Downhole camera surveys were conducted in July 2016 at the Durango processing site and in April 2016 at the Shiprock site.
[b] All samples were analyzed for uranium, sulfate, nitrate as NO_3, remaining major anions and cations (sodium, potassium, calcium, magnesium, alkalinity, and chloride), dissolved and total iron, and dissolved and total organic carbon.

3.1 Field Methods

Specific Conductance and Temperature Profiling

SC and temperature profiles were taken prior to chemical sampling. Consistent with methods used during the Phase I field investigation, at each well, profiles were obtained by slowly lowering a sonde down the well, stopping at each 0.5 ft interval. The sonde was left at the target depth until SC and temperature readings were stable (usually about half a minute), at which time the SC, temperature, time, and depth were recorded.

Two types of sondes were used during this effort: a Solinst TLC Meter Model 107 (used for most wells) and an In-Situ Aqua TROLL 200 probe (used only for wells greater than 100 ft deep). SC probes were calibrated with potassium chloride solutions at the beginning of the day or upon arrival at the site and were then checked at least several times more, throughout the day. If readings were unstable or inconsistent with the historical record, probes were recalibrated. Calibrations were typically within 5% of the potassium chloride standards.

Depending on the well diameter, it was sometimes necessary to remove downhole equipment before conductivity profiling and sampling. The downhole equipment included dedicated sample tubing or bladder pumps. In the Shiprock site floodplain wells, SOARS sensors, including water level transducers or conductivity probes, were also removed. Care was taken during equipment removal to minimize disruption to the water column. Downhole equipment was removed at least 2 days before profiling and sampling activities began, to allow groundwater in the well to re-equilibrate. At deeper Durango processing site wells, dedicated bladder pumps were removed at least 3 days before profiling.

Chemical and ^{222}Rn Sampling

Once SC and temperature (SCT) profiling was complete, if the well diameter allowed it, the probe was left in the bottom of the well to minimize any additional mixing that would occur during the retrieval of the probe. Sampling began with the use of a peristaltic pump (for wells less than 25 ft deep) or, for deeper wells, a bladder pump. Samples were collected at 1 ft intervals, starting at or near the well bottom and progressing upward as the sample tubing was slowly raised to each target depth. Pumping rates were generally between 50–150 milliliters per minute (mL/min).

To minimize disturbance to the water column, a thin tube was used to collect 50 mL for each sample in plastic vials. Tubes with inner diameters of 0.125 inches and 0.17 inches were used for peristaltic and bladder pumps, respectively. The thin tube also allowed for a minimal amount of purge between samples. At least one tubing volume was purged between each sample before collection of the next sample began. Samples were kept cool in an ice chest until they were placed in a refrigerator at the laboratory.

Although dissolved ion concentrations were of interest in this study, samples were not filtered in the field. This was for three reasons: (1) the logistics of collecting multiple samples from a well would have resulted in delays before the samples were filtered, which could cause mineral precipitation due to oxidation; (2) some constituents (e.g., uranium) may be partly removed by the act of filtering such small samples; and (3) the low flow rates used for sampling generally resulted in clear samples with minimal suspended solids.

Radon-222 profiling, like chemical profiling, was done using low-flow sample collection procedures. Peristaltic pumps operate by suction lift and produce a vacuum. Because radon is a dissolved gas, care was taken to avoid forming a vapor phase during sampling and analysis. Therefore, slow pumping rates were used during ^{222}Rn sample collection to ensure that no air bubbles were introduced into the sample.[3] Despite these precautions, on occasion, dissolved gases and small air bubbles were observed in a few samples; each instance of this was noted in field records. Due to ^{222}Rn's short half-life (3.8 days), samples were transported to the laboratory for analysis within 24 hours of sampling.

Downhole Video Profiles

Downhole well videos were conducted in the spring and summer following the chemical profiling—in April 2016 on the Shiprock site floodplain and in June 2016 at the Durango processing site. The purpose of this effort was to verify screen placement and identify any mineralization or fouling that might cause restricted flow. Results of this effort are documented in Appendix B.

High-Volume Purge Methods for Select Shiprock Site Floodplain Wells

In the introductory example for Shiprock site well 0618, Figure 3b illustrated how sample results may have been affected by changing from high-volume purge (3–5 casing volumes) to low-flow sampling methods. Although not the focus of this report, mid-screen samples were collected using high-volume purge methods in 6 of the 36 wells sampled for this study. After the SCT profile and incremental chemical sampling was performed, a minimum of 3 casing volumes of groundwater was removed. After water levels equilibrated, SCT profiles were obtained first and then samples of 250 mL were taken from the mid-screen depths for analysis of the remaining parameters.

3.2 Laboratory Methods

Phase II samples were analyzed in AS&T's Environmental Sciences Laboratory in Grand Junction, Colorado. In the laboratory, samples were analyzed for pH using a gel-filled glass electrode and for alkalinity using a sulfuric acid titration to pH 4.6. Portions of each sample were filtered through 0.45 micron (µm) filters. From this aliquot of filtered sample, approximately 10 mL was acidified to a pH < 2 using nitric acid. The filtered and acidified splits were analyzed for sodium, calcium, magnesium, potassium, and iron by inductively coupled plasma–optical emission spectrometry (ICP-OES). The remaining filtered, but unacidified sample was run for chloride, nitrate (as NO_3), sulfate, and dissolved nonpurgable organic carbon. Chloride, nitrate, and sulfate were analyzed by ion chromatography. Due to iron precipitation (and the potential for uranium to be absorbed to the precipitates) in several samples, a 10 mL aliquot of unfiltered sample was acidified to a pH < 2 using nitric acid. This split was then analyzed for uranium, using a Chemcheck kinetic phosphorescence analyzer, and iron by ICP-OES. The remaining unfiltered, unacidified sample was used for the analysis of nonpurgable organic carbon using a Shimadzu TOC-L instrument.

[3] A more detailed discussion of ^{222}Rn sampling and data interpretation is found in *Determining Flow Dynamics in Monitoring Wells with Radon-222: Applications at Legacy Uranium Mill Sites* (DOE 2016b). Based on their findings, both ^{222}Rn sampling methods—using peristaltic or bladder pump—are suitable for this study.

Radon-222 was analyzed by liquid scintillation counting using a PerkinElmer Tri-Carb 3110TR instrument. Fifteen milliliters of sample was placed in a 20 mL glass scintillation vial with 5 mL of PerkinElmer Opti-Fluor O scintillation cocktail. To minimize loss of radon gas, care was taken to limit sample exposure to air. Samples were counted for 100 minutes and daughter nuclides were ingrown by letting the samples rest for at least 240 minutes before counting (DOE 2016b). The detection limit for ^{222}Rn using this method is approximately 25 picocuries per liter (pCi/L).

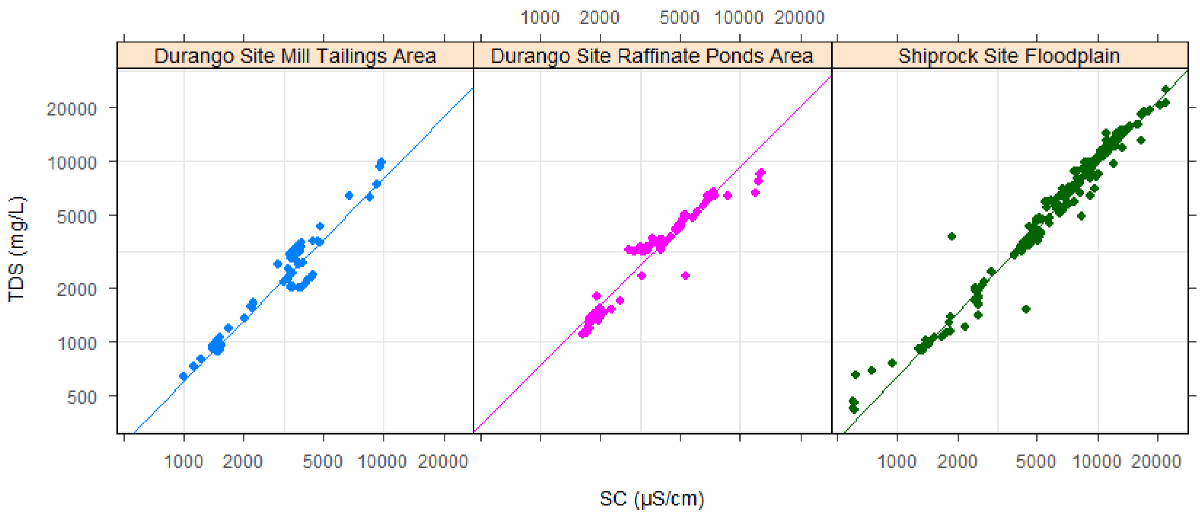
Sample data quality was assessed by calculating the charge-balance error (CBE) for all 691 samples collected and analyzed. One check of data quality is to determine whether an aqueous solution or water sample is electrically neutral. In theory, the sum of the negative charges (anions) should equal the sum of the positive charges (cations). Imbalances can occur in cases of analytical errors, unanalyzed dissolved ions, or, in some cases, using unfiltered samples with high suspended solids content. The CBE, or anion/cation balance, is calculated as the difference between the anions and cations (units of milliequivalents per liter), divided by the sum of the anions and cations. For Durango processing site samples, CBEs were generally less than 5% for 20 of the 24 wells profiled. For Shiprock site floodplain samples, CBEs were less than 5% for 60% of the wells and between 5% and 10% for the remainder. Of the 691 samples analyzed for this study, all had CBEs ≤10%, indicating generally good quality of the chemical analyses.

3.3 Analyte Selection and Data Analysis Methods

Analyte Selection

All Phase II samples were analyzed for two primary contaminants common to most LM UMTRCA sites: uranium and sulfate. Uranium is of most interest from a monitoring, modeling, and risk perspective. Sulfate, a major anion, is another primary indicator of milling-related contamination and, therefore, frequently monitored. Because SC is an indicator of salinity, it was important to understand the variables accounting for the variation in the SC profiles. Therefore, samples were analyzed for the remaining cations and anions: sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), alkalinity, chloride (Cl), and nitrate (as NO_3).

To illustrate the relationship between SC and salinity, Figure 7 plots log-SC versus log-total dissolved solids (TDS), a common measure of salinity. TDS concentrations were derived by summing the concentrations of all constituents dissolved in the water sample. As shown, the relationship between SC and TDS is fairly linear, so SC is often used as a proxy for TDS. Also evident is that groundwater underlying the Shiprock site floodplain is more saline than that at the two areas of the Durango processing site. Average and maximum TDS concentrations in Durango processing site wells were 2547 mg/L and 9807 mg/L, respectively (corresponding to a mean and maximum SC of 3404 µS/cm and 12,700 µS/cm, respectively). In contrast, TDS ranged up to 24,994 mg/L in Shiprock site wells, with a mean of 6689 mg/L, about 2.6 times greater than TDS at the Durango processing site.



Notes:
TDS was calculated based on concentrations of the major ions (alkalinity, calcium, chloride, potassium, magnesium, sodium, and sulfate), dissolved organic carbon, dissolved iron, and nitrate as NO_3. Data from four Durango processing site wells with significant drawdown are excluded from this plot due to the mismatch in sample depths (initial SC versus subsequent chemical samples).

Figure 7. Specific Conductance Versus Total Dissolved Solids in Phase II Study Wells

Radon-222 was analyzed in a third of the monitoring wells profiled in Phase II to better understand the flow dynamics (e.g., water entry points) within those wells. A natural tracer (i.e., not related to contamination), ^{222}Rn has a high natural abundance in groundwater, is chemically inert, and is radioactive with a short half-life of 3.8 days. Bartlett and Morrison (2009) used ^{222}Rn to determine residence times of groundwater in a permeable reactive barrier used to intercept a groundwater uranium plume at LM’s Monticello, Utah, Processing Site.

Radon-222 occurs naturally in aquifers by emanation from the parent nuclide radium-226, which is a natural solid-phase component of the alluvial sediments. Radon-222 emanation ceases, due to lack of radium, when groundwater enters the wellbore and the dissolved ^{222}Rn begins to decay. The measured ^{222}Rn concentrations can then be used to estimate the length of time that the groundwater resided in the well. Its short half-life limits determination of residence times to about 3 weeks. Water that is constantly replenished is likely to be more representative of groundwater in the aquifer. Higher ^{222}Rn concentrations (e.g., >200 pCi/L) typically denote these high-flux areas. Conversely, water in stagnant zones has had longer residence in the well and may reflect intrawell processes such as density separation. The longer the residence time, the lower the ^{222}Rn concentration (DOE 2016b).

Because detectable concentrations of dissolved iron might indicate a reducing environment, this constituent was analyzed along with total iron. For this study, the dissolved iron component is considered most useful, as it is more mobile and, thus, more reflective of the chemical state of the groundwater. The total iron fraction is less meaningful, as it would be influenced by turbidity or colloids in the well. It was analyzed mainly to determine whether there was any iron in solution at all (to better understand the dissolved iron results). In most samples analyzed for this study, dissolved iron was either below detectable levels (0.050.1 mg/L) or < 0.2 mg/L, suggesting that groundwater at both the Durango and Shiprock sites is generally oxidized.

Dissolved organic carbon (DOC) and total organic carbon (TOC) were analyzed for several reasons. First, the oxidation-reduction (redox) reactions that commonly affect the concentrations of inorganic contaminants at LM sites (e.g., uranium and nitrate) are often microbially mediated, signifying that subsurface organic carbon in one form or another is the electron donor (e.g., Puls and Deutsch 2002). Organic carbon concentrations might also indicate natural leaching of the Mancos Shale, a marine-derived source of organic carbon (DOE 2011). Several wells profiled in this study with high SC are screened partially or solely in the Mancos Shale.

Although temperature could be useful to evaluate in some cases (e.g., for near-river wells), consistent with the Phase I report, it was not evaluated in Phase II. In many wells, a temperature gradient with depth is probably more reflective of seasonal issues (differences between atmospheric and groundwater temperature) than related to aquifer conditions.

Data Analysis and Visualization Approach

Phase II of this study yielded 921 analyte profiles for all sites and wells combined (60 wells × 15 parameters + 21 ^{222}Rn profiles). To focus the analysis, only a subset of these profiles is discussed in the main body of this report. Plots of SC, uranium, sulfate, and ^{222}Rn profiles are provided and discussed for all wells in Sections 3–5. For the remaining variables, profile results are provided graphically in Appendixes C–E.

In addition to the variable-specific plots, for each site, the wells with the most interesting or representative profiles were selected for discussion. Examples are wells with large variation in analyte profiles, notable chemical signatures or correlations warranting further examination, or wells where the vertical profile indicated a potential for erroneous interpretations of routine monitoring results. In the case of the Durango processing site, the wells selected for discussion (i.e., those with highly variable SC and contaminant profiles) were the exception rather than the rule. Because the majority of Shiprock wells profiled had notable variation in the vertical profiles, the discussion focused on a subset of wells representing different profile signatures (e.g., within-screen variation, sump variation) as described in Section 5.4.

As discussed in Section 2.1, in Phase I of this study, the CV was useful in quantifying inter- and intrawell variation in SC, both within and between sites. As such, it also served as the basis for Phase II site selection (DOE 2015). Although initially calculated for each Phase II well-specific variable profile, ultimately the CV was not useful when applied to multiple variables and wells. The CV is still a fairly good indicator of variation in the profile for a given parameter, but in most cases, comparison of variation *between* variables was not facilitated using this measure. Therefore, variation in analyte profiles is qualitatively assessed using the data visualization approaches introduced in Section 4.2.2. Rather than attempting to quantify or compare variation between multiple parameters, the analysis focuses on the correlations or associations between variables as discussed below.

A major goal of this study was to determine whether the observed vertical variation in SC applies to site-related contaminants (namely uranium) or other groundwater constituents. To visualize these relationships, scatterplot matrixes were developed to illustrate correlations between all variable combinations in a pairwise fashion. To evaluate the potential for using SC as an indicator of uranium concentrations, plots of SC versus uranium were also developed for each well profiled in this study. These approaches are explained in detail in Section 4.2.3, as are caveats associated with these approaches. Although the study plan (DOE 2016d) anticipated the use of multiple regression methods, quantifying relationships between variables in this manner was not useful due to the complex nature of this data set. Every well is different with respect to stratigraphy, screen placement, spatial and historical context, and a combination of other factors that precluded meaningful statistical modeling.

Most data plots and related graphics presented in this report were developed using R versions 3.4.2 or 3.4.3 (R Core Team 2017) and the following related packages:

- the tidyverse, version 1.2.1 (Wickham 2017)
- lattice, version 0.20-35 (Sarkar 2008)
- latticeExtra, version 0.6-28 (Sarkar and Andrews 2016).

Of the numerous packages comprising the tidyverse, ggplot2 (Wickham 2009) was used most extensively (https://cran.r-project.org/web/packages/tidyverse/index.html).

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4.0 Durango, Colorado, Processing Site Phase II Results

The Durango processing site is a former uranium-ore processing facility located approximately 0.25 mile southwest of the central business district of Durango, Colorado. The site consists of two hydrologically and geologically separate areas, shown in Figure 8: (1) the mill tailings area, the setting of former uranium-ore milling and storage of mill tailings, and (2) the raffinate ponds area, where liquid process wastes were impounded during milling operations. Because these areas are geologically distinct, they are treated separately in this report.

Phase I SC profiling took place at both areas in late June 2014. Phase II SC and chemical profiling was conducted in August and September 2015. During that period, 13 wells were profiled at the former mill site area and 11 wells were profiled at the former raffinate ponds area (Figure 8). Four of the mill tailings area wells profiled—0622, 0629, 0857, and 0866—are considered background wells for the site (DOE 2014c). These wells were included in the Phase II study to assess whether the stratification found in Phase II chemical profiles was unique to wells impacted from former milling activities.

4.1 Site Description

Uranium and vanadium ores were milled at the Durango processing site from 1949 through 1963 (DOE 2002b). Surface cleanup of the site, entailing the removal of approximately 2.5 million cubic yards of tailings and contaminated soils, was performed from 1986 through 1991. Groundwater beneath both the mill tailings and raffinate ponds areas is contaminated with uranium and associated constituents as a result of these former milling operations. Both areas are adjacent to the west bank of the Animas River. Groundwater in the mill tailings area flows through alluvial gravel, sand, and clay that overlie a bench of low-permeability Mancos Shale bedrock. The raffinate ponds area is underlain by siltstone, sandstone, shale, and coal formations in the Mesaverde Group. Groundwater flow in this area of the site is mostly through fractured bedrock. Additional supporting information can be found in site historical documents (DOE 2002b; DOE 2008; DOE 2014c) and on the LM website at https://www.lm.doe.gov/Durango/Processing/Documents.aspx.

4.2 Mill Tailings Area

SC and chemical profiles from 13 wells in the mill tailings area were obtained in August and September 2015 (Figure 9). A simplified schematic of the mill tailings area monitoring well construction information is provided in Figure 10. The primary purpose of this figure is to illustrate the variability associated with geology and well configuration alone. For example, within this 40-acre bedrock-supported terrace, wells have different screen lengths (ranging from 5 to 20 ft) and they are screened in different formations—some in the alluvium only, several in both the alluvium and the Mancos Shale, one (0632) solely in the Mancos Shale, and another (0863) in the colluvium. Detailed well construction logs and other site data can be found on LM's Geospatial Environmental Mapping System (GEMS) website at https://gems.lm.doe.gov/#site=DUP.

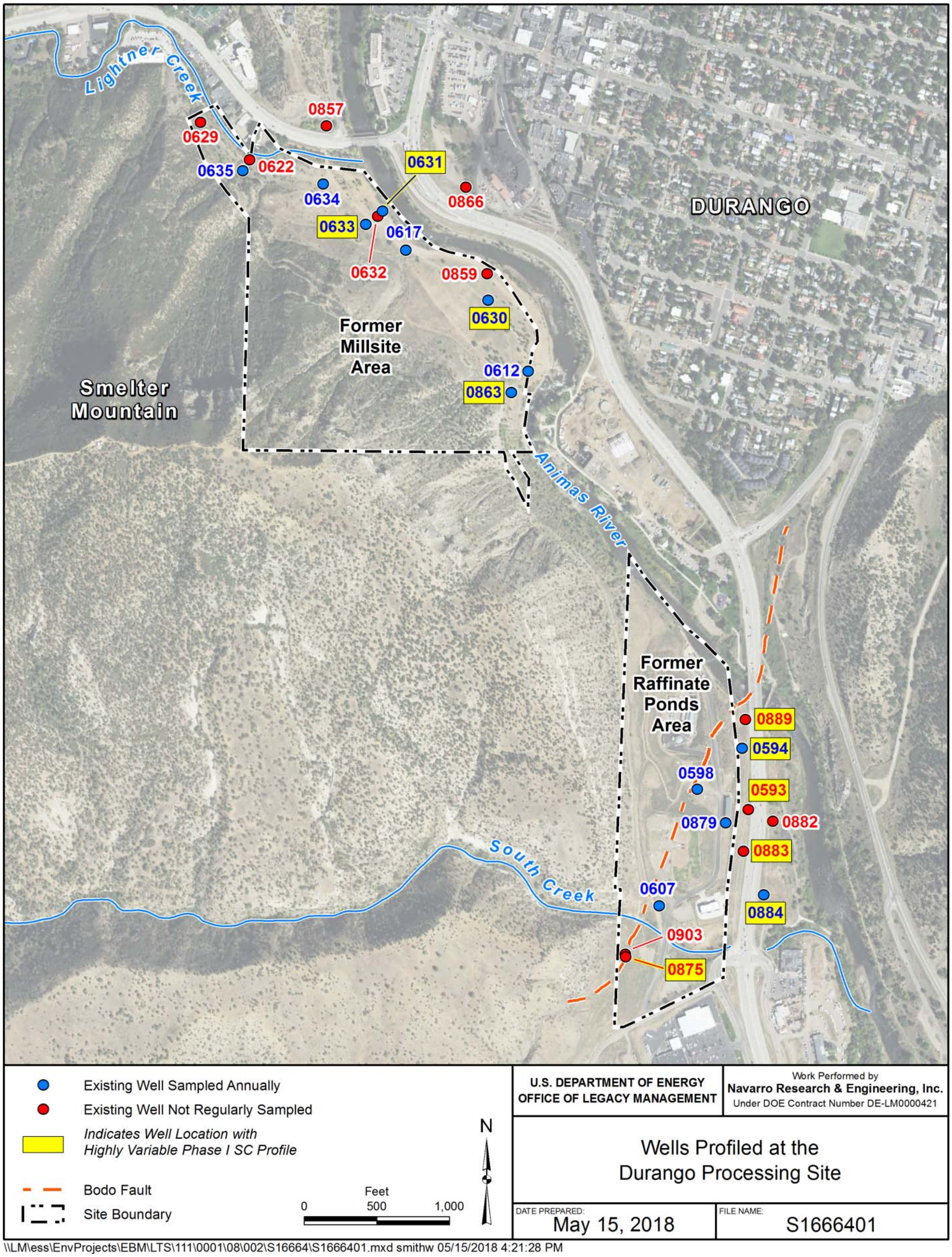
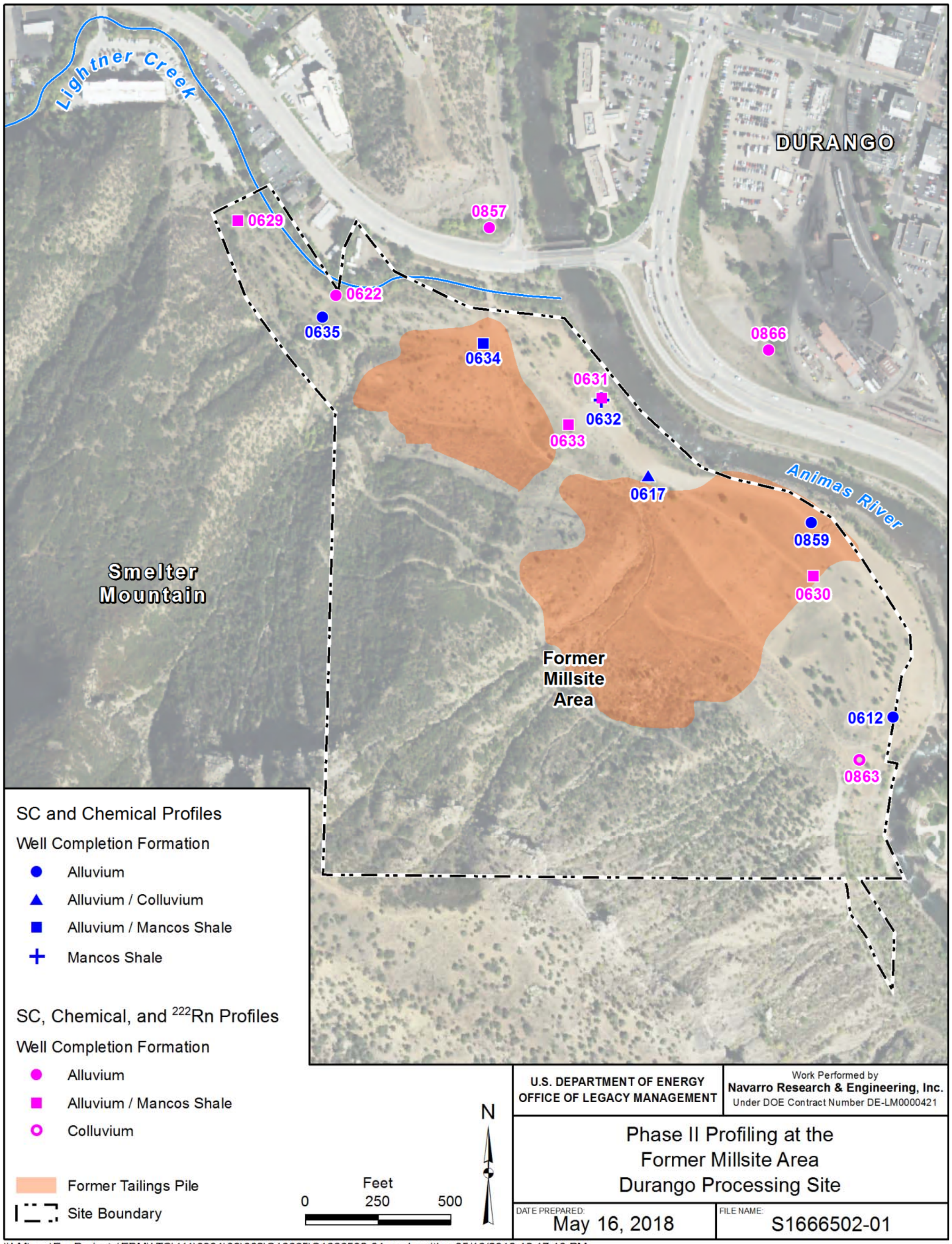
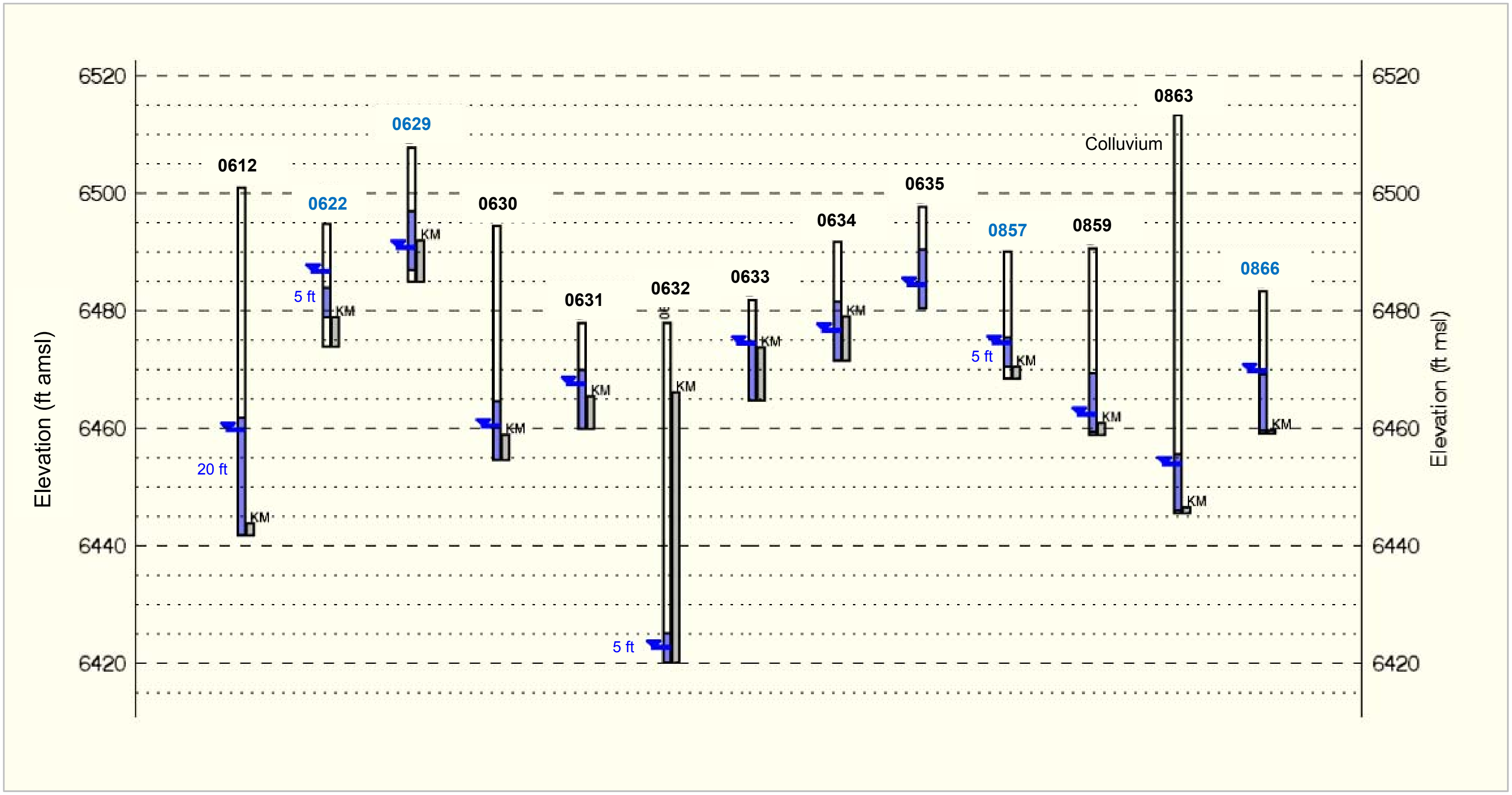


Figure 8. Wells Profiled at the Durango Processing Site, August–September 2015



Note: Although well 0617 was profiled in Phase I (DOE 2015), there was insufficient water to sample in Phase II. Northernmost wells 0622, 0629, and 0857 and well 0866 (across the Animas River) are considered background wells for this area of the site.

Figure 9. Wells Profiled at the Durango Processing Site Mill Tailings Area



Notes:

Inverted blue triangles show the June 2017 groundwater elevations (except where noted).
Black rectangles show the well casings; well screens are shaded blue.
The top of bedrock—the KM contact—is shown to the right of well screen. Well screens are 9.5–10 ft long except where noted above.
Wells are plotted in order of well ID and, therefore, do not reflect horizontal location. Four of the alluvial wells (0622, 0629, 0859, and 0866) are considered background wells (DOE 2014c).
Corresponding well construction logs are available on the LM GEMS website (https://gems.lm.doe.gov/#site=DUP).

Abbreviations:
amsl = above mean sea level
KM = Mancos Shale

Figure 10. Well Construction Information for Durango Processing Site Mill Tailings Area Wells

4.2.1 Hydrogeologic Overview

The uppermost aquifer at the mill tailings area is shallow and consists mostly of poorly sorted colluvium derived from Smelter Mountain. Part of the shallow aquifer also consists of Animas River and Lightner Creek alluvium. The saturated zone is generally less than 10 ft thick, unconfined, of limited areal extent, and of low yield (less than 150 gallons per day [DOE 1996]). The colluvium and alluvium are underlain by low-permeability Mancos Shale bedrock. Approximately 70 ft of colluvium overlies bedrock along the base of Smelter Mountain. These deposits thin eastward to about 15 ft, close to the Animas River. Depth to groundwater increases from about 5 ft on the river terrace to about 60 ft near the mountain base. Groundwater flow is generally to the southeast, parallel to the Animas River, at an average gradient of approximately 0.02 feet per feet (ft/ft). Hydraulic conductivity of the colluvium and alluvium ranges from 10 to 70 feet per day (ft/d). Whereas the alluvial aquifer receives inflow from Lightner Creek and from the Animas River, the colluvium in the mill tailings area is recharged primarily by runoff from Smelter Mountain and infiltrating precipitation.

4.2.2 Specific Conductance and Analyte Profile Results

Phase II of this study yielded 203 analyte profiles for the mill tailings area alone (13 wells × 15 parameters + 8 ^{222}Rn profiles). Due to the volume of data, this section focuses primarily on results for SC, uranium, and sulfate and on the subset of wells characterized by the greatest degree of stratification or variation within the vertical profiles. Detailed results are provided in Appendix C, which includes all associated data: plotted by analyte (Appendix C-1) and by well (Appendix C-2).

<u>Specific Conductance Profiles</u>

In Phase I of this study, nearly half of the wells within or downgradient of the former mill area had SC profiles with high variation (CVs ≥ 0.1) (DOE 2015). To introduce the Phase II results, Figure 11 plots SC by depth measured in all 13 mill tailings area wells profiled in August–September 2015. Wells are listed in order of high to low variation as defined by the CV calculated for the Phase I (June 2014) SC profiles, which are also shown in this figure.

Figure 11 includes two distinct types of plots. Figure 11a plots SC profiles relative to screen placement and, if applicable, the Mancos Shale or bedrock contact. Screens are denoted by the blue lines to the left of each plot. The *x*- and *y*-axis scales are unique for each well, allowing greater resolution of corresponding SC profiles. Figure 11b shows the same data, but with common scales for both SC and depth (surface elevations differ, as shown in Figure 10). Points are color-coded to denote the portion of the well where the measurement was taken: the upper casing (●), screened interval (●), or sump (●) (below the screened interval).

Although Figure 11a conveys the most information (showing screen and formation details), Figure 11b is useful because the common scales facilitate interwell comparisons. For example, it is more readily apparent that wells 0630, 0631, and 0633 have the most variable SC profiles. SC profiles with relatively little variation are also more easily identified in Figure 11b. For example, although Figure 11a indicates a steady increase in SC with depth in well 0859, the lower plot illustrates that these changes occur over a relatively small (in this case, 70–80 µS/cm) interval. The wells with the highest salinity (e.g., well 0633) are also more easily identified in the lowermost plot of Figure 11 (the mean SC for this well subset was 3271 µS/cm).

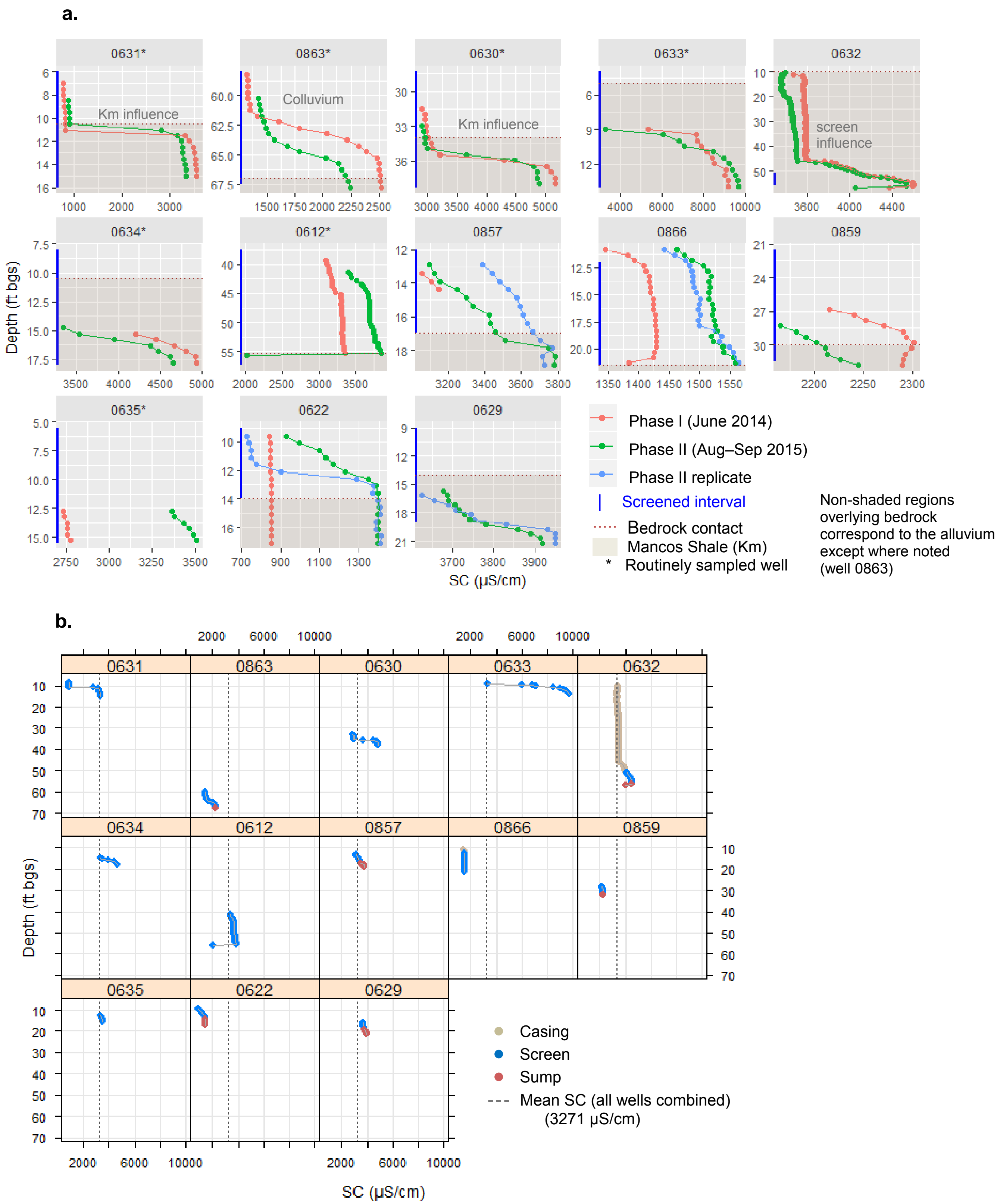


Figure 11. Specific Conductance Profiles in Durango Processing Site Mill Tailings Area Wells

(a) Phase I and Phase II SC profiles, with unique scales and screen intervals shown; (b) SC versus depth, with common scales (Phase II results only). In (a) and (b), wells are ordered based on descending variation in Phase I SC profiles.

Although the Phase I (June 2014) and Phase II (August–September 2015) SC profiles were obtained at different times of the year under different groundwater and river flow conditions (early summer high runoff versus late summer), overall, the results are similar (Figure 11). The wells with the greatest degree of variation in Phase I—wells 0631, 0863, 0630, 0633, and 0632—have similar profiles in Phase II. The most obvious temporal difference is apparent in upgradient well 0622, which had a flat (low-variation) SC profile signature in Phase I, but was somewhat stratified in Phase II. This well, along with well 0635, is influenced by recharge from Lightner Creek (Figure 9) (DOE 2002b), a factor that may account for the temporal differences observed (i.e., the more uniform profiles in June vs. those measured in August–September).

Phase II results confirm those reported for Phase I (DOE 2015): for the five wells with the greatest variation in SC profiles noted above, SC increases with depth, sometimes markedly, within the screened interval. All of these wells are screened at least partially in the Mancos Shale; well 0632 is screened solely in the Mancos Shale. In three wells—0630, 0631, and 0863[4]—SC increases at or near the bedrock (Mancos Shale) contact, but then appears to stabilize. For each mill tailings area well profiled in Phase II, Table 2 summarizes key information, including zone(s) of completion, the Phase I CV, number of samples collected, and observations regarding the SC, chemical, and ^{222}Rn profile results.

Uranium, Sulfate, and Other Analyte Profiles

Another goal of this study was to examine whether the observed stratification in SC also applies to other constituents, in particular, uranium and sulfate. To provide a generalized overview of findings, Figure 12 plots corresponding results for all analytes. The purpose of this figure is to help identify (1) wells with the highest or most variable trends for a given parameter (e.g., wells 0630 and 0633); (2) parameters with generally little or no variation (e.g., nitrate); and (3) outlier results (dissolved iron results in a few samples). Results are excluded for northernmost background wells (0622, 0629, 0857, 0866) to allow better examination of profiles for the wells of interest—that is, to facilitate differentiation of profiles between wells. Because use of a linear scale masks lower-magnitude results (e.g., uranium concentrations in well 0634), the bottom portion of this figure (Figure 12b) plots the same data for key variables using a logarithmic scale. Table 3 summarizes corresponding observations for each parameter or analyte category.

As expected, given the relationship between SC and dissolved ions, concentrations of sulfate and the remaining major anions and cations (most notably sodium and chloride) vary vertically in most wells (Figure 12). Uranium concentrations also vary with depth—in a number of cases decreasing (rather than increasing), in contrast to corresponding SC profiles. Profile results for total and dissolved fractions of iron (Fe) and organic carbon show no obvious pattern or trend and nothing compelling in terms of explaining the observed variation in SC or other parameters.

The low (mostly below detection limit) dissolved iron concentrations likely indicate oxidized conditions in groundwater (but this by itself is not conclusive). Nitrate concentrations were low or below detection limit values (nitrate is not a contaminant at this site). Although pH varied, it was mostly within the neutral range (7.3–8.6). The most alkaline conditions were found in Mancos Shale well 0632, with a pH range of 8.3 to 8.6.

[4] According to the well log for well 0863, the Mancos Shale contact is at a depth of 67 ft below ground surface (bgs). However, there is an indication that the weathered Mancos Shale contact may be as shallow as 60 ft bgs, which would explain the shift in SC profiles at or near this depth shown in Figure 11.

Table 2. Summary of Wells Profiled at the Durango Processing Site Mill Tailings Area, Phase II Study

Well	Zone of Completion	Phase I SC CV[a]	Phase II Sample *n*[b]	Comments
0612[c]	AL	0.03	14	Relative to other wells, little variation in SC and other analytes with depth. Consistent with routine monitoring results, this well had the highest uranium concentrations in the profile (1.3–1.6 mg/L). It also has the longest screen (20 ft) of those profiled.
0622	AL	0.005	8[d]	Upgradient (background) well. The only well with apparent correlations between SC, uranium, and the major ions (Appendix C).
0629	AL-KM	--	5[d]	Upgradient well not profiled in Phase I.
0630[c]	AL-KM	0.26	4[d]	This well had only 4–5 ft of saturated thickness, all of which was within the Mancos Shale bedrock. Uranium concentrations varied over an order of magnitude, from 0.01 to 0.34 mg/L, and decreased with depth. Radon-222 concentrations were low (<47 pCi/L), suggesting that flow is restricted in the screened zones adjacent to Mancos Shale.
0631[c]	AL-KM	0.67	7[d]	As is true for well 0630, uranium concentrations decrease with depth. Low uranium levels appear to correspond to stagnant zones based on the ^{222}Rn profiles.
0632	KM	0.08	28	Screen effect: SC increased within the short (5 ft) screened interval; measurements were stable through the overlying blank casing. Screened entirely in bedrock, variation in SC is attributed to high sodium chloride level characteristic of Mancos Shale. Uranium concentrations were very low in this well (<0.003 mg/L).
0633[c]	AL-KM	0.14	5[d]	Despite the AL-KM designation, this well is screened almost entirely in the Mancos Shale. In both Phase I and II, SC increased steadily through the saturated portion of the screened interval. This trend was also seen for sulfate and other major ions, but not for uranium.
0634[c]	AL-KM	0.06	4	Limited saturated thickness; nothing notable in profiles, except that uranium concentrations decrease with depth.
0635[c]	AL	0.005	3	Too few samples to evaluate; results show mostly random variation (statistical noise).
0857	AL	0.02	6[d]	Background well hydrogeologically separate from the site. Nothing notable in profile.
0859	AL	0.01	3	Too few samples to assess. Apparent increase in depth for most major ions, that is, there is some variation, but over a limited range.
0863[c]	Colluvium	0.28	6[d]	Screened in the colluvium, this well had a highly variable SC profile. Low (<30 pCi/L) ^{222}Rn concentrations in all samples indicate limited groundwater flow through the well screen.
0866	AL	0.02	11[d]	Background well hydrogeologically separate from the site. SC varies over only a limited range (100 µS/cm). No compelling patterns; results reflect mostly noise or random variation.

Notes:

[a] CV of Phase I SC measurements made in June 2014 (DOE 2015). In this table, CV values are formatted as follows: 0.67 High (CV ≥ 0.1); 0.06 Mid-Level (0.03 ≤ CV < 0.1) and; 0.008 Low (CV **<** 0.03).

[b] Number of samples (*n*) collected for chemical analysis. As samples were collected at 1 ft intervals, in most cases, this number roughly corresponds to the thickness of the water column at the time of profiling. Because SC profiling was conducted at 0.5 ft intervals before sampling, the number of SC measurements is about twice the sample *n* listed above for each well.

[c] Denotes well routinely sampled, for example, during annual June monitoring.

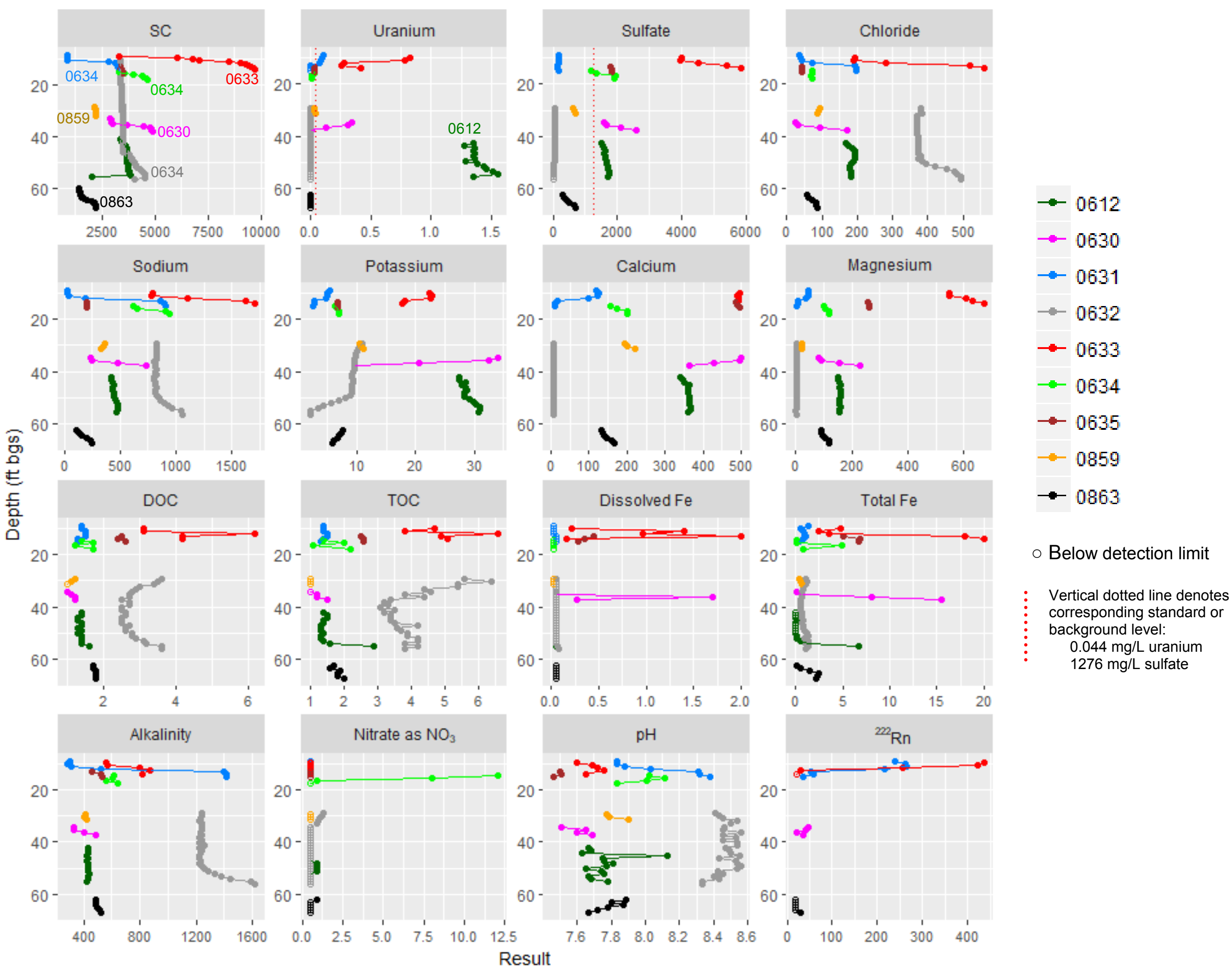
[d] Denotes that the well was also profiled for ^{222}Rn.

0622 Blue font denotes upgradient or background well as defined in DOE (2014c).

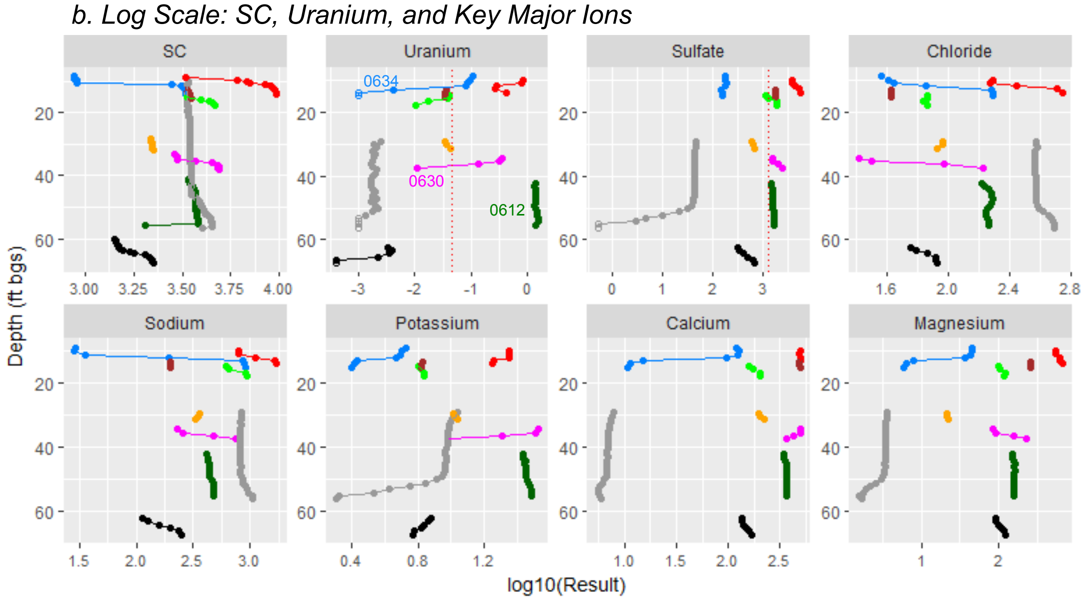
Abbreviations:

AL alluvium
KM Mancos Shale
n number of samples

a. Linear Scale, All Parameters



b. Log Scale: SC, Uranium, and Key Major Ions



Notes: All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$. Well names are listed on some plots to facilitate review (background wells 0622, 0629, 0857, and 0866 are excluded).

Figure 12. SC and Analyte Profiles for Durango Processing Site Mill Tailings Area Site Wells

Table 3. Summary of Observations by Analyte, Durango Processing Site Mill Tailings Area Wells

Parameter	General Trends
SC	Phase II profile results are generally consistent with those in Phase I. As found in Phase I, the greatest variation in the vertical SC profiles was found in wells screened partially or solely (well 0632) in the Mancos Shale. In most wells, SC increases with depth, even within the saturated portion of the screened interval. Except for background well 0622, Phase II results were generally consistent with Phase I results.
Uranium	Uranium is the primary indicator of milling-related contamination at this and other LM UMTRCA sites. The most notable variation was measured in wells 0630 and 0631, where U levels varied by 1 to 2 orders of magnitude within the screened interval. In these and other cases, in contrast to the increasing SC vertical trends, uranium concentrations decreased with depth. As has been the case historically (DOE 2014c), uranium levels were highest (but non-varying) in well 0612 (1.3–1.6 mg/L).
Sulfate	Another indicator of site-related contamination (DOE 2014c) and also one of the major ions contributing to the salinity or SC profile. In most cases, sulfate concentrations increase with depth consistent with trends observed for SC. Exceptions are well 0631 (no vertical trend) and Mancos Shale well 0632 (decreasing trend). Sulfate concentrations were highest (>4000 mg/L) in well 0633, adjacent to one of the former tailings piles.
^{222}Rn	Measured in 8 of the 13 mill tailings area wells, ^{222}Rn is a direct indicator of groundwater residence time in the well. In general, the ^{222}Rn signatures in these samples indicate a higher flux (or flow) rate in screened portions within or adjacent to the alluvium. Flow is typically restricted in the Mancos Shale and colluvium (except in limited zones, which indicate preferential or fracture flow) and also in the well sumps.
Remaining major ions	Like sulfate, magnesium was strongly correlated with SC in a number of wells. This was also true for sodium and to a lesser extent chloride. Potassium levels were generally low (<35 mg/L and in most cases <10 mg/L). More than any parameter, however, potassium was most correlated with uranium.
Nitrate as NO_3	Below detection limit (0.5 mg/L) in 7 of the 13 wells profiled. Concentrations in remaining wells were ≤12.1 mg/L, well below the 44 mg/L UMTRCA standard. Although typically associated with former milling processes, nitrate is not a contaminant of concern at the Durango processing site (DOE 2014c).
DOC and TOC	DOC was strongly correlated with TOC. In most wells, DOC concentrations were less than 2 mg/L, the mean level measured in mill tailings area groundwater samples based on historical monitoring results. Overall, the DOC and TOC profiles were erratic in this subset of wells, having no notable signature or pattern.
Iron, total and dissolved	Results for dissolved iron were below detection limit (0.05 mg/L) in 7 of the 13 wells profiled. All results were less than 4 mg/L. Total iron is of less interest and the profiles provide no noteworthy information (most results were <5 mg/L).
pH	The pH varied within the neutral range of 7.3–8.6. The only well that showed a linear trend with depth was well 0631. Well 0632, screened in the Mancos Shale, had the most alkaline groundwater (pH of 8.3–8.6).

Note:
Detailed plots of profile results are provided in Appendix C-1 for each of the 16 individual analytes.

The remaining discussion focuses on the primary indicators of site-related contamination, uranium and sulfate. To evaluate corresponding flow dynamics, ^{222}Rn signatures are also discussed for the subset of wells profiled.

Figure 13 plots uranium concentrations by depth measured in mill tailings area wells. Consistent with the layout in Figure 11, wells are listed in order of descending variation reported in Phase I (DOE 2015). As shown in this figure, in most wells, uranium concentrations varied within the vertical profile to some degree. In the case of well 0612, with the highest uranium concentrations, this variation is small and probably representative of random variation (note the flat trend line in Figure 13b). This characterization also applies to the vertical uranium profile for Mancos Shale well 0632 (a classic example of statistical noise) and most upgradient wells. The greatest degree of variation in the uranium profiles was found in wells 0630, 0631, 0633, and 0634, screened in both the alluvium and the Mancos Shale, and well 0863, screened mostly in the colluvium. These locations correspond to the well subset exhibiting the greatest salinity stratification in Phase I based on the SC profiles.

However, in contrast to SC (which increased with depth), in all of these cases uranium decreased with depth within the screened interval. One explanation for this decreasing trend is that the Mancos Shale has characteristically lower uranium concentrations than the overlying alluvium. The top of the Mancos Shale is likely weathered, which could result in higher permeability in the weathered zones and increased potential for uranium migration from the overlying alluvium. In well 0632, screened entirely in bedrock, uranium was not detected or less than 0.003 mg/L. But of the wells screened in both the alluvium and the Mancos Shale, at the time of profiling, only well 0631 had groundwater in the alluvium (Figure 13). For wells where the water table is near or slightly below the contact, uranium concentrations are highest in this region, and decrease gradually with depth. In fact, the water table (as indicated by the depth of the uppermost sample) was below the top of the screened interval in all mill tailings area wells profiled except Mancos Shale well 0632 and alluvial background well 0866.

The range in uranium concentrations measured vertically in wells 0630, 0631, 0633, and 0634 is potentially large enough to impact interpretations of temporal trends (all four wells are routinely sampled). For example, in wells 0630 and 0631, uranium concentrations span an order of magnitude or more, straddling the 0.044 mg/L maximum concentration limit (MCL) established in Title 40 *Code of Federal Regulations* Part 192 (40 CFR 192), which apply to UMTRCA sites. In the screened interval of well 0630, uranium levels decreased from 0.34 to 0.011 mg/L within 4 ft. A similar trend was found in well 0631, where uranium concentrations decreased from 0.1 to <0.001 mg/L over a 7 ft distance within the screened interval. In wells 0633 and 0634, uranium concentrations vary by more than a factor of 2 within the screened interval, decreasing from 0.8 to 0.3 mg/L (well above the standard) and 0.04 to 0.01 mg/L (below the standard), respectively.

Figure 14 plots corresponding results for sulfate, a major ion and a constituent that is routinely monitored. In most cases, sulfate concentrations increase with depth, generally corresponding to SC. Exceptions are well 0631 (in which there was no vertical trend) and well 0632. In well 0632, screened solely in the Mancos Shale, sulfate concentrations are very low (<50 mg/L) relative to other mill tailings area wells profiled (Figure 14b) and are inversely proportional to SC. The high salinity in this well is attributed to a dominant sodium chloride composition that may reflect an influence of groundwater from deep, unweathered Mancos Shale characterized by elevated chloride (DOE 2011).

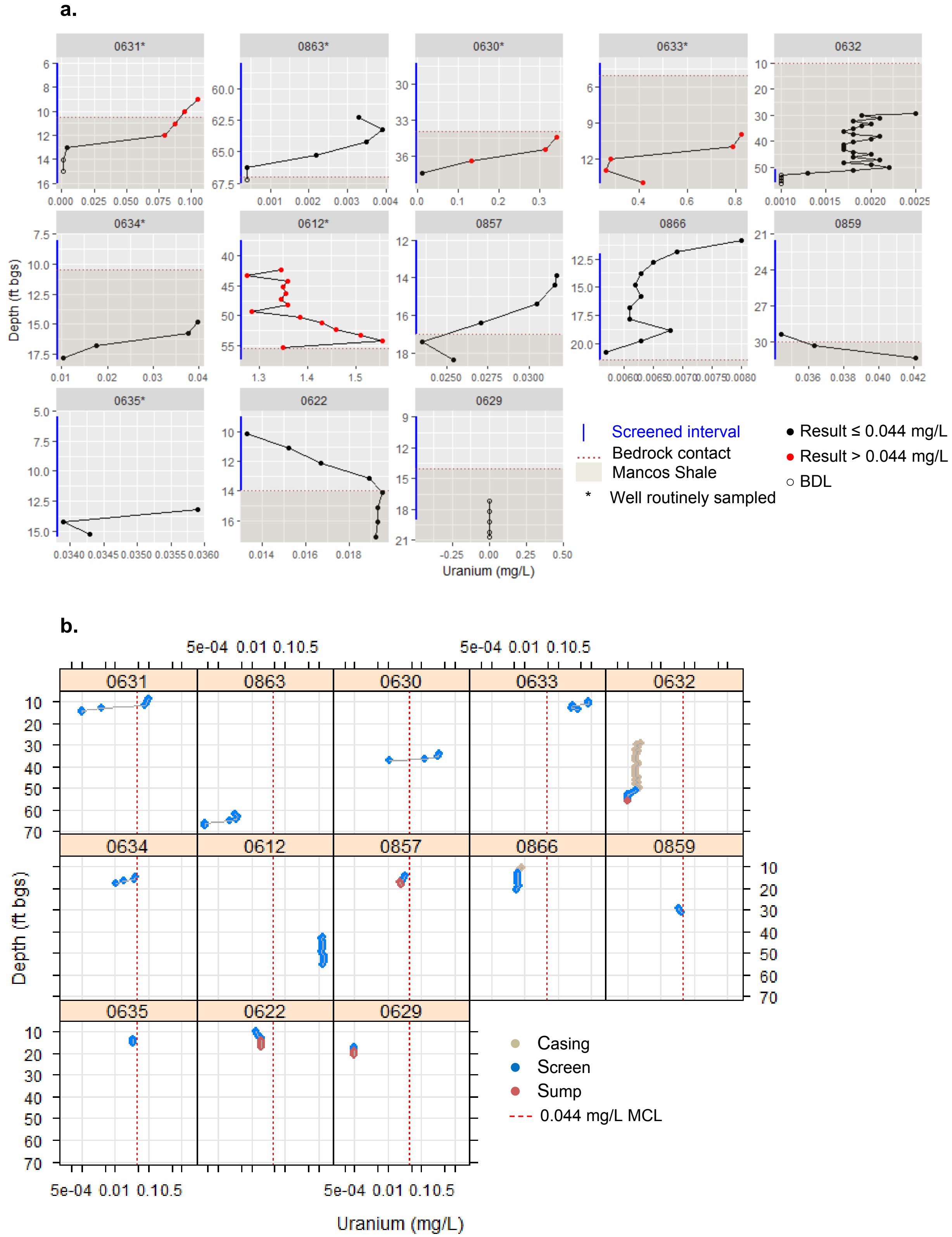


Figure 13. Uranium Profiles in Durango Processing Site Mill Tailings Area Wells

(a) August–September 2015 profiles, unique scales and screen intervals shown;
(b) Scatterplot of uranium by depth, common scales.
In both plots, wells are ordered based on descending variation in Phase I SC profiles.

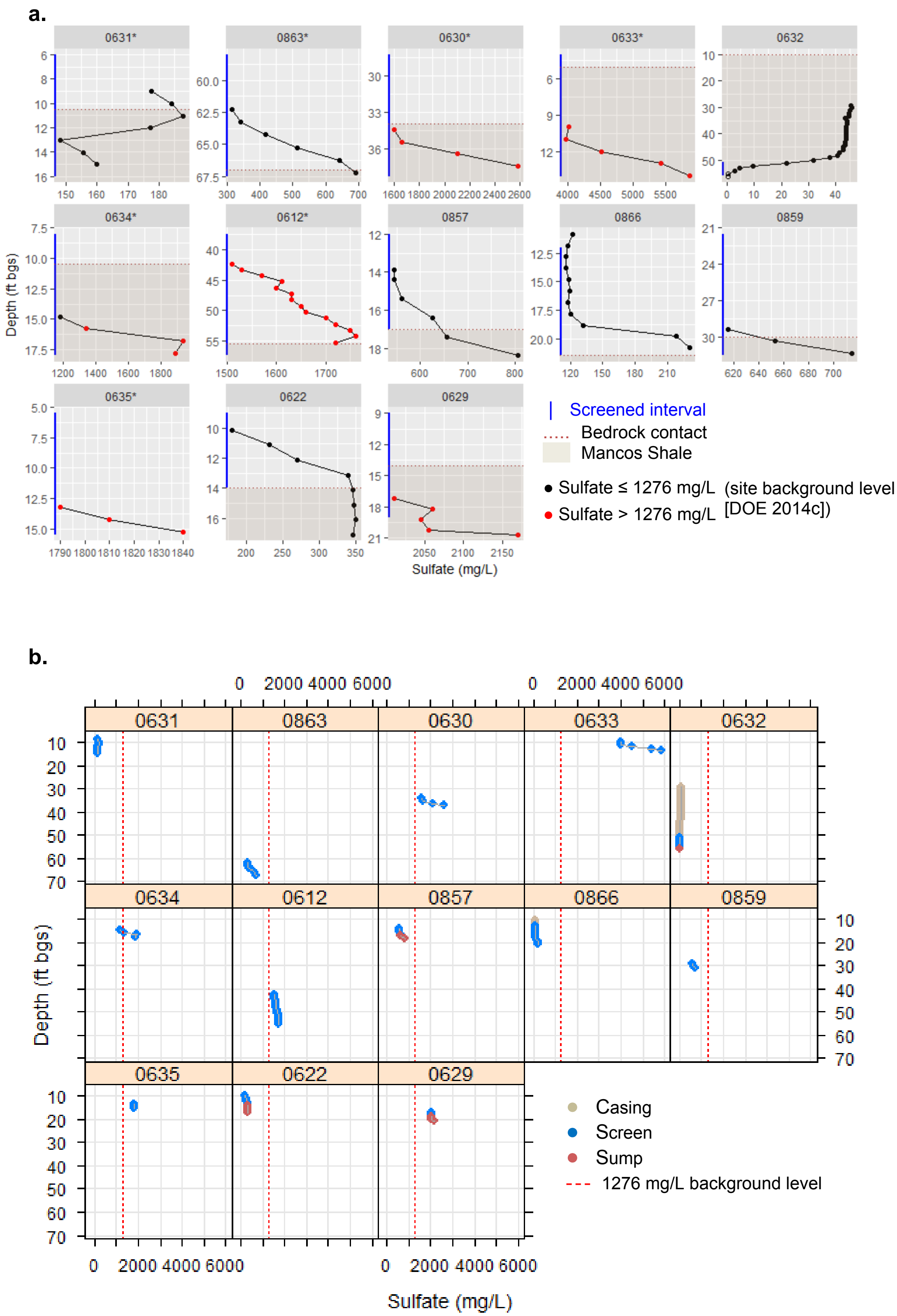


Figure 14. Sulfate Profiles in Durango Processing Site Mill Tailings Area Wells

(a) August–September 2015 profiles, unique scales and screen intervals shown;
(b) Scatterplot of sulfate by depth, common scales.
In both plots, wells are ordered based on descending variation in Phase I SC profiles.

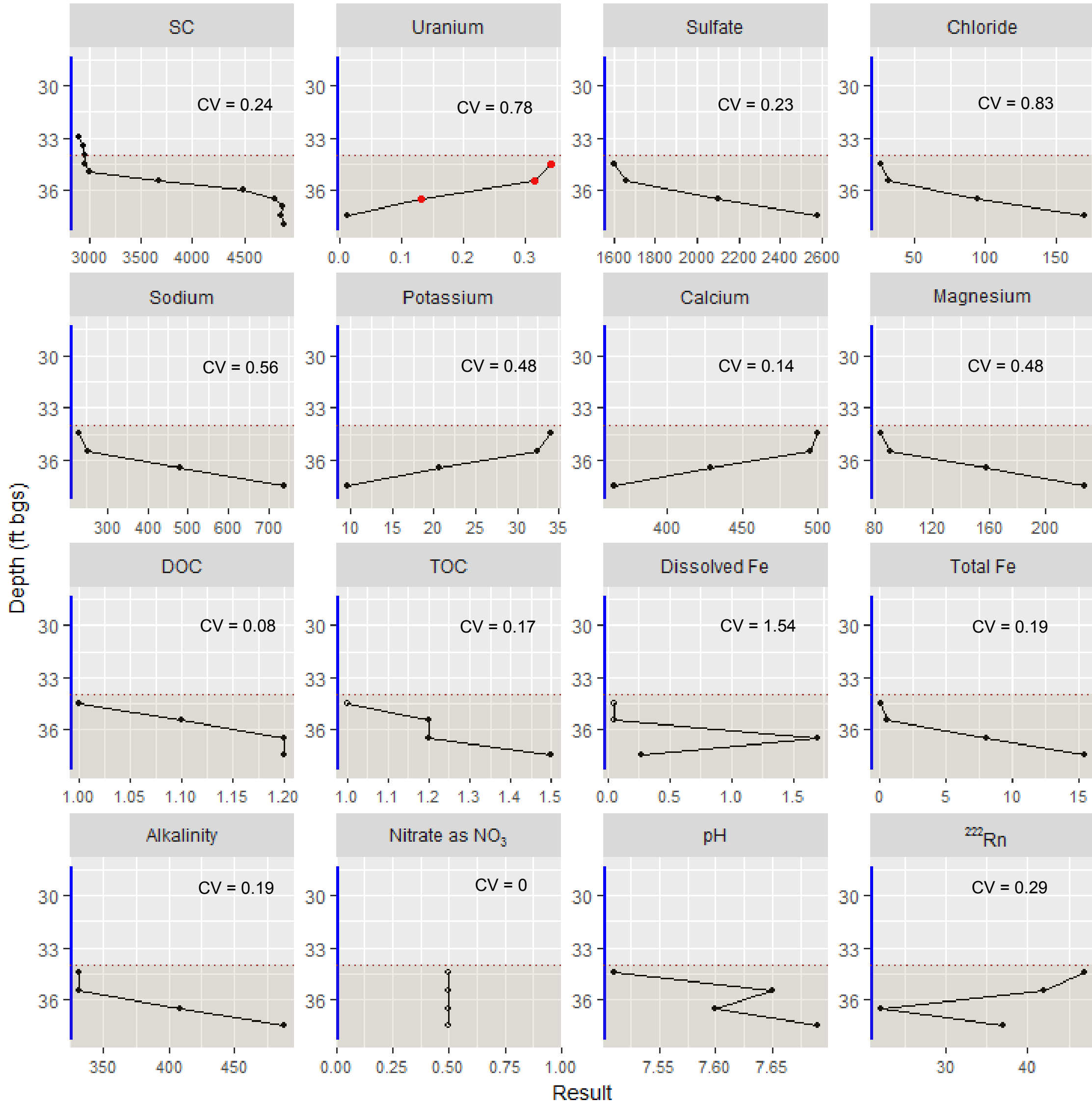
To more closely examine potential factors accounting for the trends discussed above, Figure 15 and Figure 16 plot all analyte profiles for wells 0630 and 0631. These locations were selected because of the observed vertical stratification in SC and the wide range in uranium concentrations measured within the screened interval. Also, both wells were profiled for ^{222}Rn, allowing evaluation of corresponding flow dynamics. Because similar figures were generated for all wells profiled in this study, a brief explanation is provided here. The layout in each of these figures reflects in part the relative importance of the parameter or similarity of geochemical characteristics. For example, the first panel or row includes plots for the primary variables evaluated in this study: SC, uranium, and sulfate. Like sulfate, the last variable in this row, chloride, is an anion.

The second row of Figures 15 and 16 includes the cations sodium, potassium, calcium, and magnesium, which are also potentially useful in explaining the chemistry of the SC profile. The third row includes plots for DOC and TOC and dissolved and total iron. As discussed in Section 3.3, these data could be useful in characterizing geochemical conditions and potentially explain the chemical profiles. The last row includes plots for remaining ions (alkalinity and nitrate), pH, and ^{222}Rn, analyzed to identify stagnant zones in a well.[5] Although not a contaminant at the Durango processing site, nitrate is a constituent of concern at the Shiprock site, as well as at many other LM UMTRCA sites.

For each analyte, Figures 15 and 16 also list the corresponding CV values (except for pH), used in Phase I of this study to categorize degrees of variation in the SC profiles. Plots are annotated in this manner to demonstrate why, for Phase II, these indices were not used to quantify variation. The CV is still a fairly good indicator of variation in the profile for a given parameter. For example, for well 0631, both DOC and TOC have low CV values (0.05–0.06), reflecting the small range in the profiles. However, in all cases, comparison of variation *between* variables is not facilitated using this measure. For example, when comparing mill tailings area well 0630 well profiles for SC (CV = 0.24) and uranium (CV = 0.78), one could conclude that uranium varies more than SC in this well. But that is not necessarily the case. Ultimately, initial attempts to apply the CV to all analytes and all well profiles did not yield a meaningful comparison of variation. That is, this approach did not help the interpretation of the combined profile results. Instead, we relied mainly on the data visualizations (e.g., those shown in Figures 11 through 17) and then, as presented later in this section, evaluated correlations between the variables.

The analyte profiles obtained for mill tailings area well 0630 (Figure 15) indicate an apparent correlation between SC and several of the major ions: sulfate, chloride, sodium, and alkalinity. There appears to be an inverse relationship between SC and uranium, as well as the cations potassium and calcium. Although this well is screened in both the alluvium (AL) and the Mancos Shale (KM), the top of the water table was just above the Mancos Shale interface. The low ^{222}Rn concentrations (22–47 pCi/L) indicate that water is stagnant in this region of the well. As mentioned previously, within the screened interval over a span of just 4 ft, uranium concentrations decrease from 0.34 mg/L (nearly an order of magnitude above the 0.044 mg/L standard) to 0.01 mg/L. However, the low water level in this well with regard to the alluvium/Mancos Shale contact limits the inferences that can be made about overall vertical trends.

[5] Radon-222 is plotted last in these figures and all similar ones (in Appendixes C and D) because it was only analyzed in a subset of the wells profiled in Phase II, allowing a consistent format in each well-specific figure.



| Screened interval

Bedrock (Mancos Shale) contact

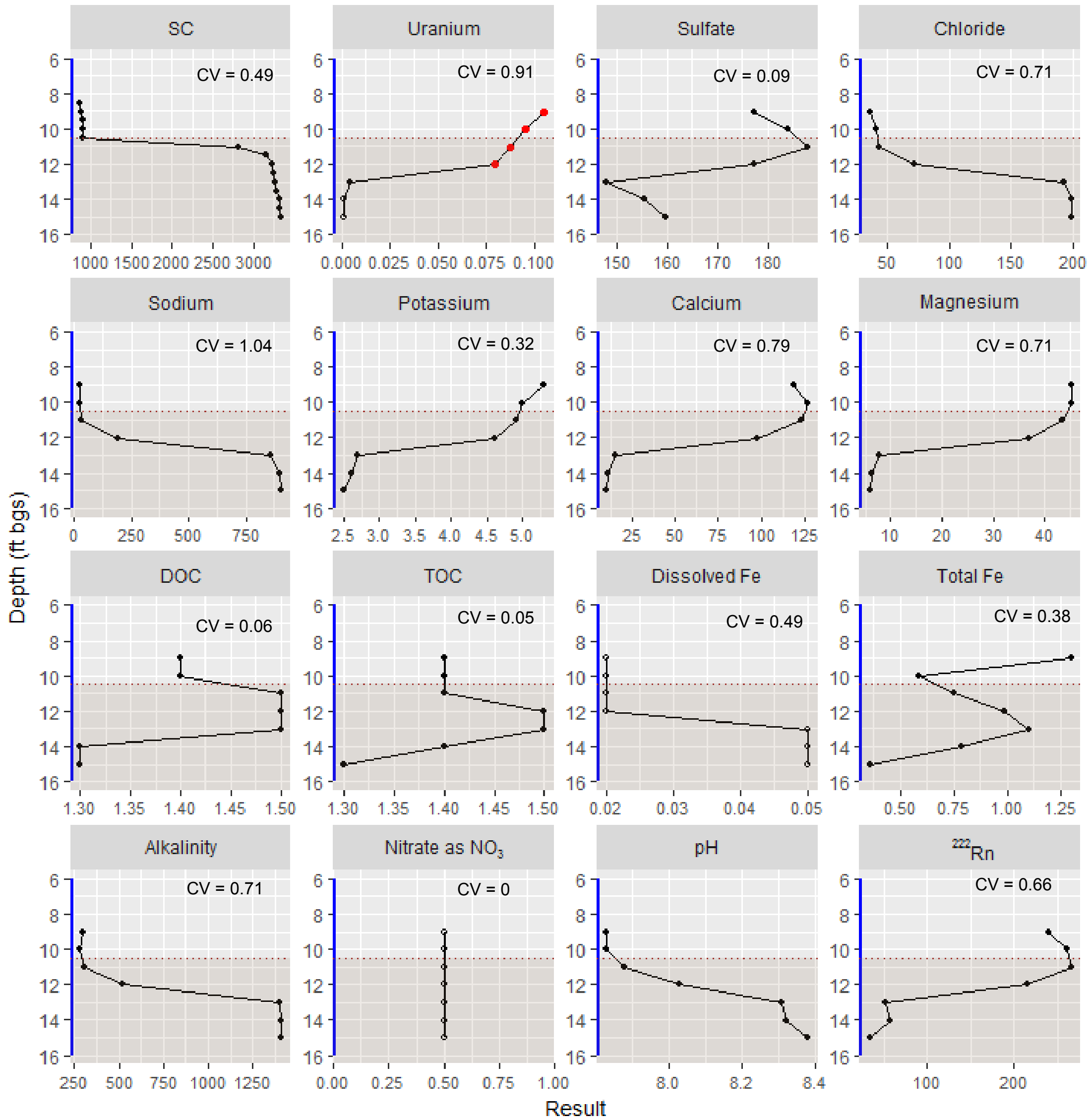
Mancos Shale

● Result exceeding corresponding 40 CFR 192 MCL: 0.044 mg/L uranium and 44 mg/L nitrate as NO_3

○ BDL

Notes:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$
The CV is the standard deviation divided by the mean of the measurements in each vertical profile.
No CV is listed for pH because the pH scale is logarithmic.

Figure 15. Variable Profiles from Durango Processing Site Mill Tailings Area Well 0630, August 2015



| Screened interval

Bedrock contact

Mancos Shale

● Result exceeding corresponding 40 CFR 192 MCL: 0.044 mg/L uranium and 44 mg/L nitrate as NO_3

○ BDL

Notes:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$
The CV is the standard deviation divided by the mean of the measurements in each vertical profile.
No CV is listed for pH because the pH scale is logarithmic.

Figure 16. Variable Profiles from Durango Processing Site Mill Tailings Area Well 0631, August 2015

The chemical signature indicated by the vertical profiles for AL-KM well 0631 (Figure 16) is slightly different. As found for well 0630, there is an apparent correlation between SC and sodium, chloride, and alkalinity. That is, these parameters best account for the salinity profile. Along with alkalinity, the high sodium chloride composition in the lowermost part of the profile (bottom of the screened interval) is probably more representative of the Mancos Shale than the alluvium. Sulfate concentrations are relatively low (about 150–200 mg/L) compared to those in well 0630 (1600–2600 mg/L), and the vertical profile is erratic with no apparent trend. There is also an apparent inverse relationship between SC and uranium, as well as three cations (potassium, calcium, and magnesium).[6]

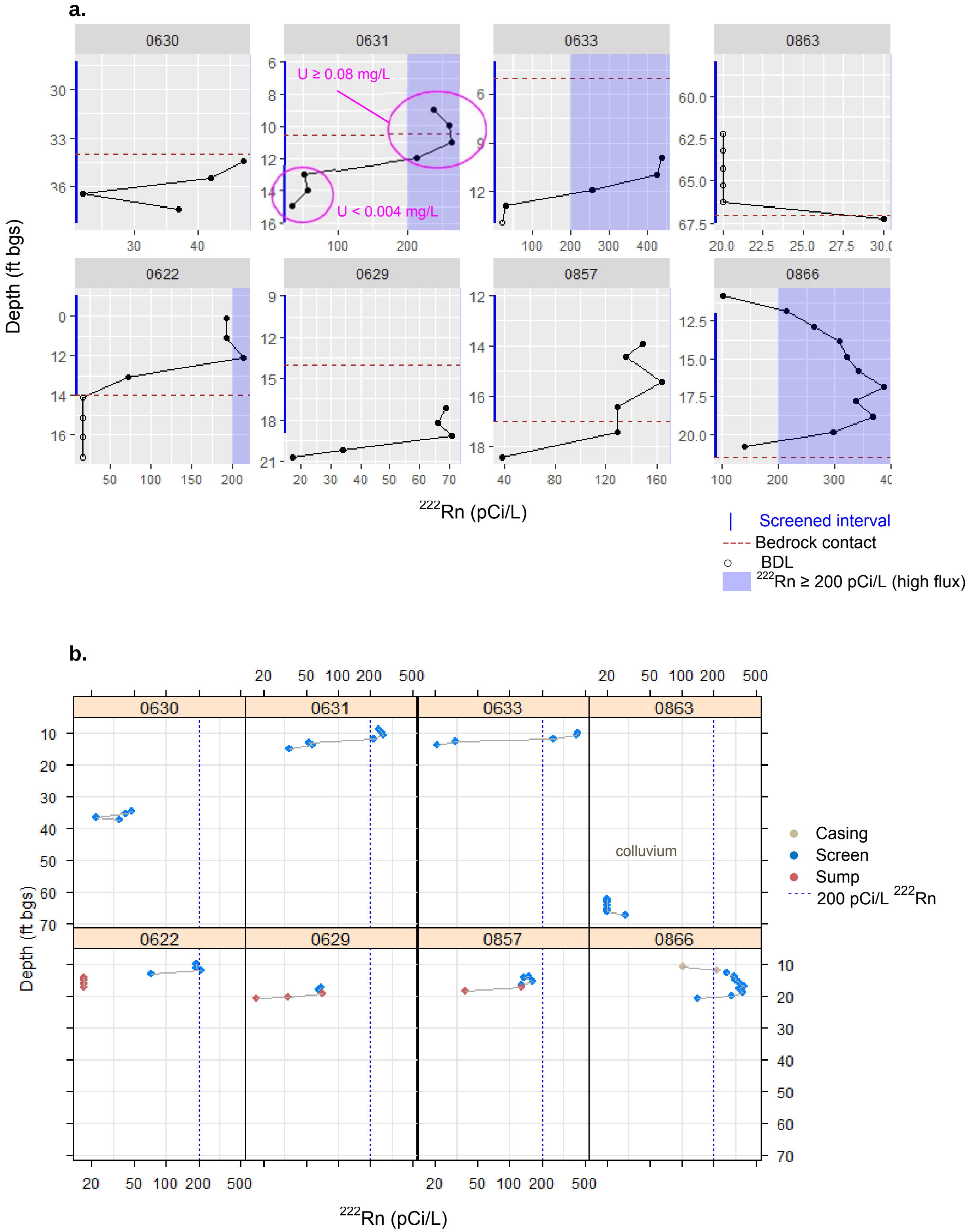
Within the screened interval of well 0631 over a span of about 7 ft, uranium concentrations decrease 2 orders of magnitude, from 0.1 mg/L in the uppermost sample in the alluvium to less than 0.001 mg/L in bedrock. The ^{222}Rn profile has a somewhat similar trend, decreasing from about 240 pCi/L in the uppermost samples (above and slightly below the bedrock contact) to 35 pCi/L in the lowermost sample. In contrast to well 0630 (Figure 15), where uranium concentrations decrease gradually, there is an abrupt drop in concentrations in well 0631 (Figure 16), coinciding approximately with the bedrock contact. Uranium concentrations are high in areas in the well with higher groundwater flux rates (in the alluvium or just below the bedrock contact), but near or below detection limits deeper into bedrock where water is stagnant.

Radon-222 Profiles

As discussed in the preceding section, ^{222}Rn was useful in distinguishing higher versus lower groundwater flux zones in wells 0630 and 0631. Radon-222 profiles were also obtained in six other mill tailings area wells, as shown in Figure 17. A natural tracer, ^{222}Rn is a direct indicator of groundwater residence time in the well (Section 3.3). Drawing upon the detailed evaluation provided in LM’s recent study of flow dynamics (DOE 2016b), ^{222}Rn profiles for mill tailings area wells are interpreted as follows:

- All four samples from well 0630 had low ^{222}Rn concentrations (≤47 pCi/L), suggesting that groundwater flow is restricted in the screened zones in the Mancos Shale.
- The upper four samples collected from well 0631 had ^{222}Rn concentrations above 200 pCi/L, coinciding with the region where uranium levels were highest (>0.08 mg/L) (Figure 16). In contrast, ^{222}Rn was <60 pCi/L in the lower three samples, where uranium levels were <0.004 mg/L. Based on these results, the four uppermost samples are probably more representative of alluvial groundwater, whereas the lower samples likely reflect influence from the Mancos Shale bedrock.
- Despite being screened almost entirely in Mancos Shale bedrock, the upper two samples from well 0633 had ^{222}Rn concentrations of about 430 pCi/L, suggesting groundwater influx from the alluvium or a weathered and higher permeability zone at the upper surface of the Mancos Shale.
- Well 0863 is screened largely in the colluvium and had low, mostly below detection limit (BDL) (<20 pCi/L), ^{222}Rn concentrations at all depths, suggesting limited groundwater flow in this formation. In the lowermost sample, ^{222}Rn increased slightly from BDL to 30 pCi/L near the colluvium–Mancos Shale interface.

[6] It is important to pay attention to scale when examining all figures in which scales are unique (e.g., Figures 15 and 16). For example, in Figure 16, although the shape of the potassium profile mimics that of other variables (e.g., uranium), the concentrations are so low (<6 mg/L) that the trend may be insignificant or coincidental rather than meaningful.



Abbreviation:
U = uranium

Figure 17. Radon-222 Profiles in Durango Processing Site Mill Tailings Area Wells, September 2015

(a) August–September 2015 profiles, screen intervals and bedrock contact shown;
(b) Scatterplot of ^{222}Rn by depth, common scales
(site wells are in top row; upgradient wells are in in second row)

Results for ^{222}Rn in upgradient wells 0622 and 0629 and wells 0857 and 0866, hydrogeologically separated from the mill site area, are summarized as follows:

- Well 0622 has a relatively typical profile with highest ^{222}Rn concentrations of about 200 pCi/L in the screened zone and levels < 17 pCi/L (the detection limit) in the sump.
- Well 0629 had only 4–5 ft of saturated thickness, all of which was within the Mancos Shale bedrock or in the well sump. All samples had low ^{222}Rn concentrations (< 70 pCi/L); the highest concentrations were within the screened zone.
- Well 0857, located offsite and north of Lightner Creek (Figure 9), is screened entirely in alluvium. In this well, ^{222}Rn concentrations ranged from 129 to 149 pCi/L in samples collected within the screened interval. Levels then dropped to 38 pCi/L in the lowermost sump portion of the well.
- Well 0866, offsite and east of the Animas River, is screened entirely in alluvium. This well had the highest ^{222}Rn concentrations measured in Phase II of this study (with a maximum of 386 pCi/L).[7] The curvature in the vertical profile indicates the highest flux (^{222}Rn > 300 pCi/L) in the mid-screen portion of the well.

The ^{222}Rn profile results for the four background samples indicate the utility of ^{222}Rn to assess the relative residence time of groundwater in a well, regardless of location or contamination history.

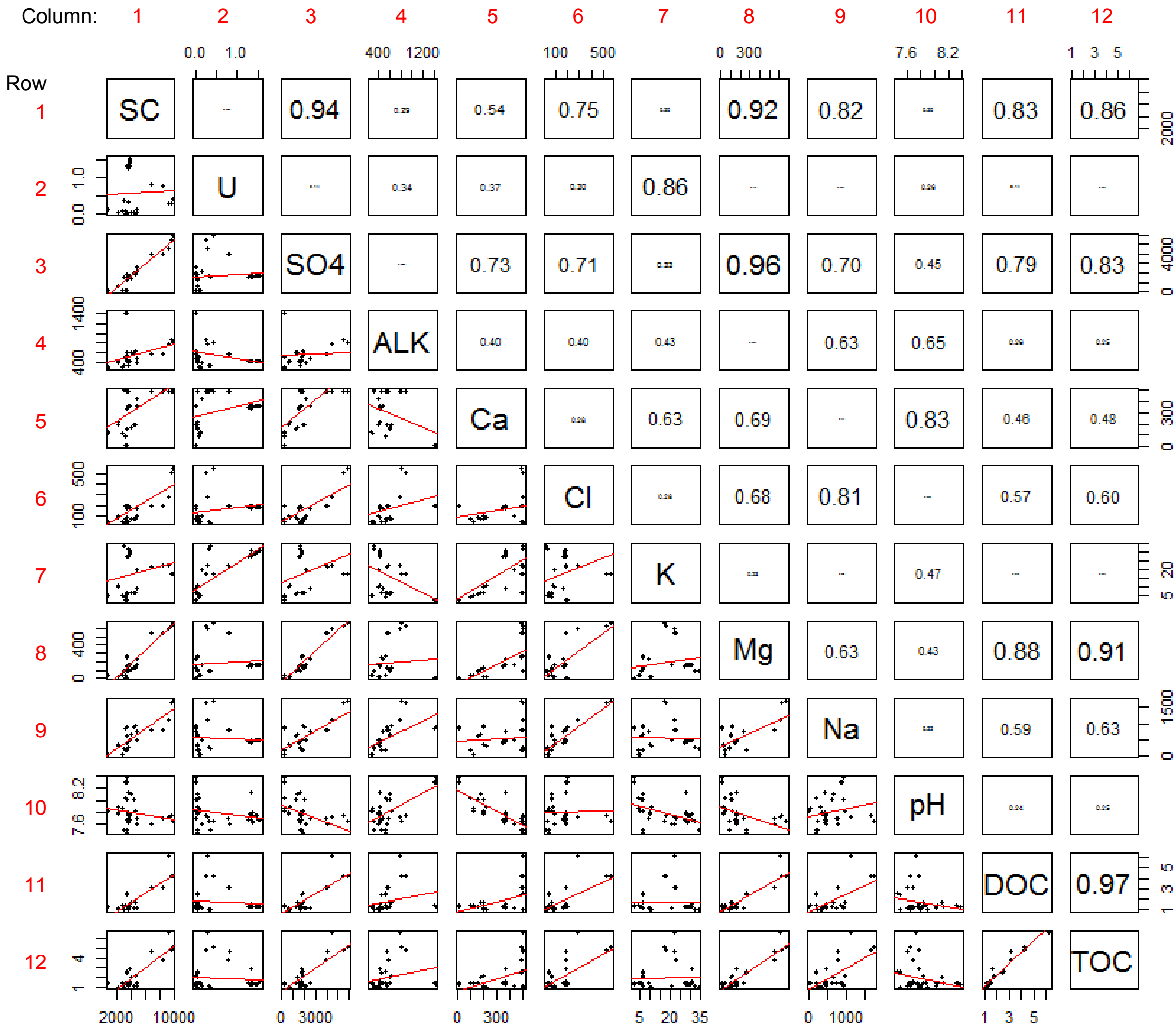
In summary, the ^{222}Rn signatures determined in mill tailings area wells suggest the following about groundwater flow dynamics in these wells: (1) groundwater often flows through well screens adjacent to alluvium, (2) groundwater flows though some well screens adjacent to Mancos Shale bedrock, but in other cases flow is restricted by the Mancos Shale, and (3) groundwater flow is typically restricted in well sumps.

4.2.3 Relationships Between Specific Conductance and Other Variables

A goal of this study was to determine whether the observed vertical variation in SC applies to site-related contaminants or other groundwater constituents. That is, is there a correlation between SC and uranium or other milling-related site contaminants? Additionally, what ions or constituents best explain the chemistry of the salinity, thereby accounting for the variation in SC measured in the profiles? Scatterplot matrices were generated to best visualize the pairwise relationships among the 15–16 variables measured during the Phase II study.

As illustrated in Figures 11 through 14 and the supporting data plots in Appendix C, every mill tailings area well was somewhat different in terms of the combined analyte profile shapes and trends. Given these interwell differences, the assessment of correlations might be more revealing if done on a well-specific basis. This was not possible, however, due to limited saturated thickness in many of the wells, 3–4 ft in some and < 10 ft in most (Table 2). Therefore, to identify potential sitewide trends, data from seven onsite (i.e., non-background) wells screened solely or partially in the alluvium—wells 0612, 0630, 0631, 0633, 0634, 0635, and 0859—were combined to generate the scatterplot matrix in Figure 18.

[7] The highest ^{222}Rn concentrations were measured in raffinate ponds area well 0884.



0.94 Absolute value of Pearson's product-moment correlation coefficient (*r*). Font size proportional to magnitude of *r*.
Upper-right triangle: Corresponding correlation coefficients for each variable pair.
Lower-left triangle: pairwise scatterplots, where — is linear trend line.

Notes:
Scatterplot generated using the **pairs()** function from *R*'s base graphics, *R* version 3.4.2 (R Core Team 2017).
Although this matrix shows the linear trendline for each pairwise combination, in many cases, the relationships are *not* linear.
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.
Scales shown on *x*- and *y*-axes of figure.

Abbreviations:
U = uranium; SO4 = sulfate; ALK = alkalinity; Ca = calcium; Cl = chloride; K = potassium; Mg = magnesium; Na = sodium

Figure 18. Scatterplot Matrix of Key Variables, Mill Tailings Area Well Subset
Onsite wells screened solely or partially in the alluvium combined:
wells 0612, 0630, 0631, 0633, 0634, 0635, and 0859

For each variable combination (e.g., SC versus uranium), the lower-left triangle of Figure 18 includes a scatterplot with linear trend lines. The upper-right triangle of this figure lists the corresponding correlation coefficient *r*, which quantifies the strength of the linear association between each variable pair. In each panel, the font size is proportional to the absolute value of *r*; the closer this value is to 1, the stronger the correlation and the larger the font size.

For example, the first panel in the second row of Figure 18 plots SC versus uranium. The trend line is nearly horizontal (essentially flat) and there is significant data scatter about the regression line, indicating a nonlinear relationship. The correlation is so weak for this combined data set that *r*, with a value of 0.04, is not decipherable in the figure (row 1, column 2).[8] In contrast, there is a strong linear relationship between SC and sulfate (row 3, column 1) and less data scatter about that line. The corresponding correlation coefficient, 0.94, is shown in row 1, column 3. Other variable combinations that appear to be correlated with little scatter about the regression line (i.e., a fairly strong linear relationship), include:

- SC and magnesium, $r = 0.92$ (row 1, column 8)
- Sulfate and magnesium; $r = 0.96$ (row 3, column 8)
- Magnesium and TOC, $r = 0.91$ (row 8, column 12)
- DOC and TOC, $r = 0.97$ (row 11, column 12)

Other variable pairs with apparent but less significant correlation include:

- SC and sodium, $r = 0.82$ (row 1, column 9)
- SC and TOC, $r = 0.86$ (row 1, column 12)
- Uranium and potassium, $r = 0.86$ (row 2, column 7)

To simplify the presentation, four variables were excluded from the scatterplot matrix in Figure 18: dissolved and total iron, nitrate, and ^{222}Rn. Dissolved iron was excluded because most results were below detection limits. Total iron was excluded because it would merely reflect the total colloids in the well. Nitrate was present at low levels (often BDL) and is not a contaminant at the site. Radon-222 was excluded because it was only analyzed in a subset of these wells, resulting in a limited data set.

To examine correlation coefficients for variable pairs with weaker correlations (e.g., between SC and uranium), Figure 19 presents a similar scatterplot matrix, but in a different "heatmap" format. Both versions are used in subsequent sections of this report. This figure excludes the scatterplots; instead, the presentation focuses solely on the magnitude and actual (versus absolute) value of *r*. As such, positive associations (shown in red) can be distinguished from negative correlations (shown in blue). Similar to the presentation in Figure 18 (with differing font sizes), the stronger the association, the darker the color (thus the term "heatmap"). For example, relative to the preceding scatterplot matrix (Figure 18), in Figure 19 it is more apparent that pH is negatively correlated with most variables, especially calcium.

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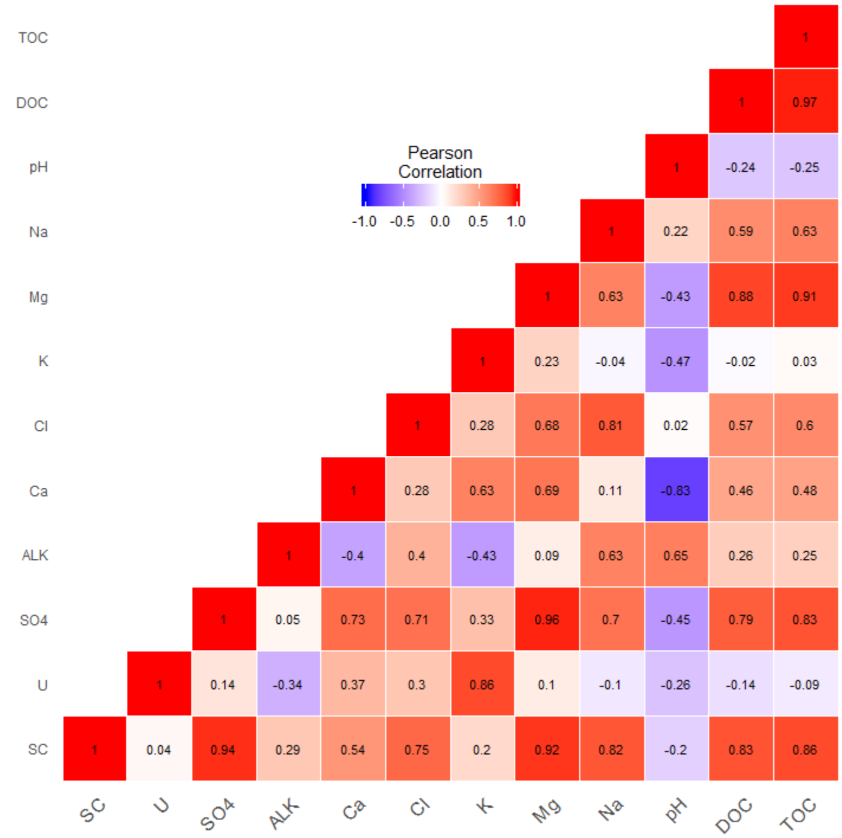
[8] In Figure 18, if the correlation coefficient *r* is listed in row *x*, column *y*, then the corresponding scatterplot is shown in row *y*, column *x*.

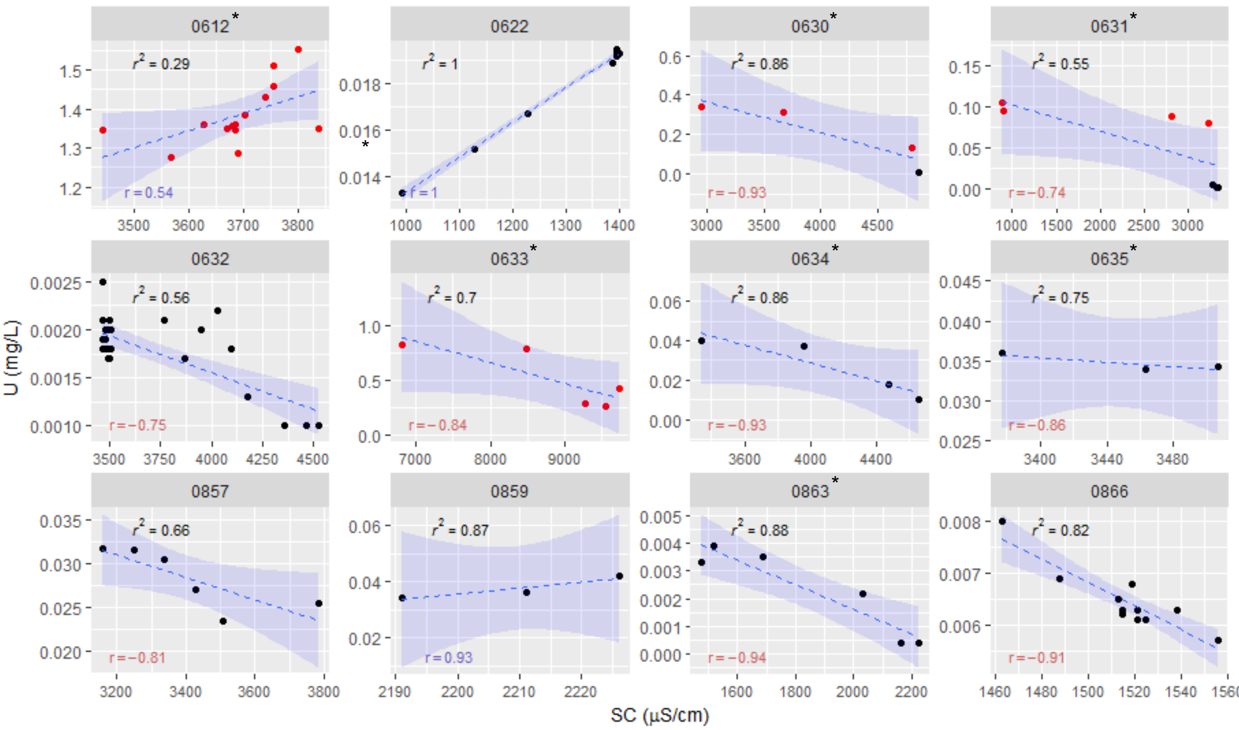


Abbreviations:
U = uranium; SO4 = sulfate; ALK = alkalinity; Ca = calcium; Cl = chloride; K = potassium;
Mg = magnesium; Na = sodium

Figure 19. Heatmap Corresponding to Figure 18 Scatterplot Matrix

Even when combining wells with different profiles and patterns, the variation in salinity for wells screened solely or partially in the alluvium can be explained by the sulfate and magnesium signatures. Similar strong associations between these variables were also found for well 0632, screened solely in the Mancos Shale. The correlation between SC and uranium in this combined well subset is very weak ($r = 0.04$). To determine whether this weak association between SC and uranium was universal (applying to all mill tailings area wells), well-specific correlations were evaluated as discussed below.

As a major focus of this report was to evaluate the potential for using SC as an indicator of uranium concentrations, Figure 20 plots SC versus uranium for all mill tailings area wells profiled in Phase II. For each well, both r and the corresponding coefficient of determination (r^2) are shown. Both values are used to summarize the strength of the relationship between variables. In the case of r^2, one variable is the response variable and the other is an explanatory variable (so, in a sense, this is a modeling approach). For example, in background well 0866, characterized by an apparent inverse linear relationship, the r^2 value of 0.82 means that the explanatory variable (SC) explains 82% of the variation in the response variable (uranium). It is important to note, however, that r^2 is an approximation of the relationship between two variables *only* when the relationship is linear.



Linear regression line and corresponding 95% point-wise confidence interval (CI)
● Red points denote uranium concentrations > 0.044 mg/L 40 CFR 192 MCL
* Denotes well that is routinely sampled.

Notes:
The color of *r* indicates either a positive or negative association between the two variables.
Background well 0629 is excluded from this figure, as uranium was not detected in the profile samples.

Figure 20. SC Versus Uranium in Mill Tailings Area Phase II Vertical Profiles

Similar to the plotting approach used later in this report, for each well shown in Figure 20, uncertainty in the linear fit (regression line) is reflected in the form of a 95% point-wise confidence interval (CI) represented by the blue shaded area.[9] In cases where data are sparse (e.g., well 0859), these bands are wider.

As shown in this Figure 20, there is not a strong, consistent linear relationship between SC and uranium. In 9 of the 12 wells profiled, uranium is inversely related to SC but in most cases only moderately so. In well 0612, with the highest uranium, the correlation is positive but weak ($r^2 = 0.29$). Uranium was most closely associated with SC in background well 0622 ($r^2 = 1$). In a number of wells (e.g., well 0635), the sample number is probably insufficient to draw definitive conclusions.

Given the limited vertical profile data, a similar plot was generated using historical monitoring results for mill tailings area wells that are routinely monitored (Figure 21). In this figure, data points are color-coded to indicate the relative date: more recent samples are lighter in color. With far more data points, this analysis corroborates the aforementioned conclusion of no strong linear relationship between SC and uranium ($r^2 \leq 0.25$ in five of the six wells).

[9] http://ggplot2.tidyverse.org/reference/geom_smooth.html. Also refer to Wickham 2009.

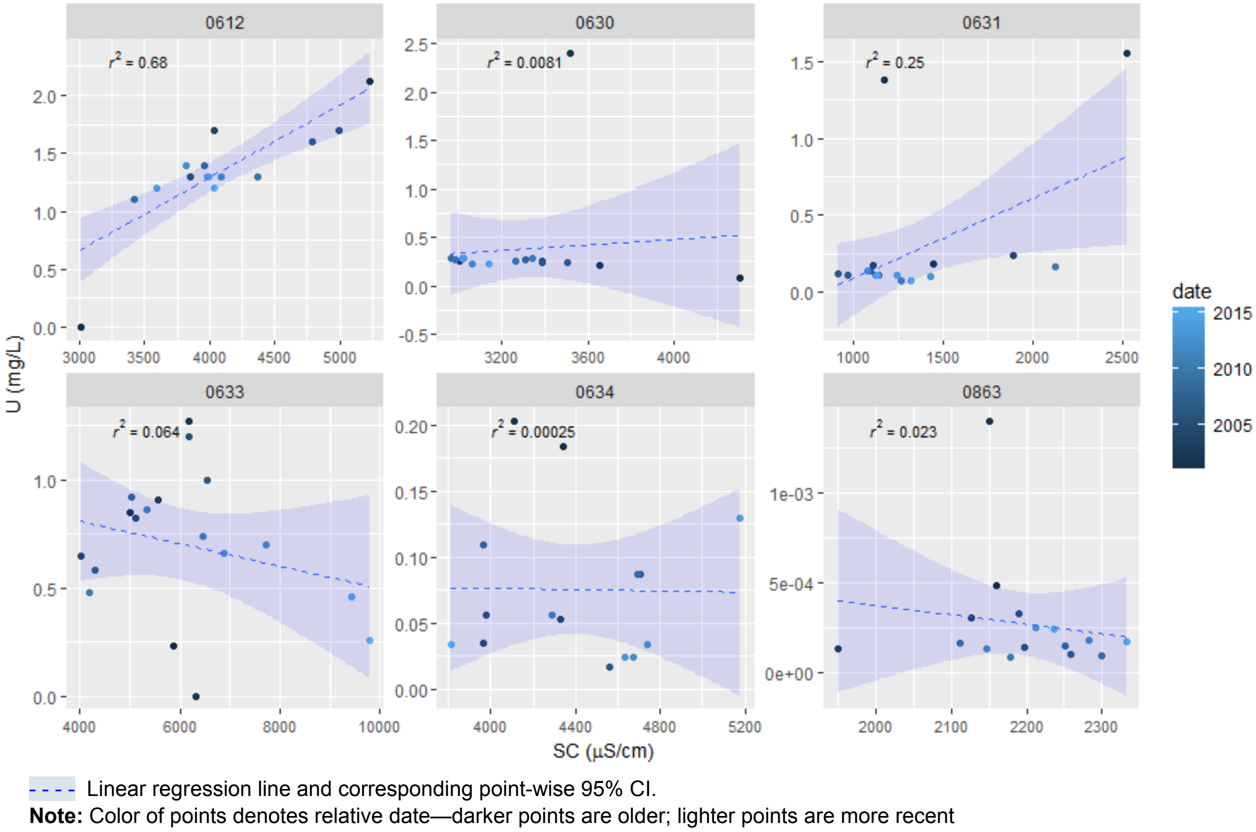


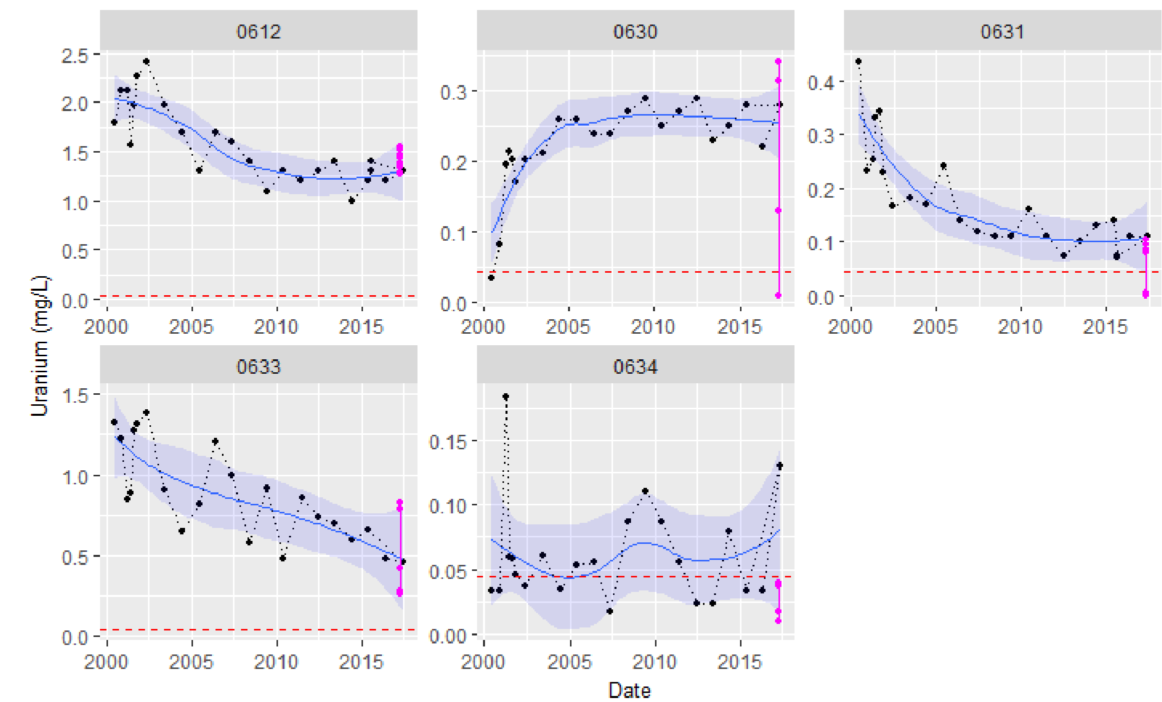
Figure 21. SC Versus Uranium in Mill Tailings Area Wells Based on Routine Monitoring: 2000–2017

4.2.4 Routine Monitoring Results Versus Vertical Profiles

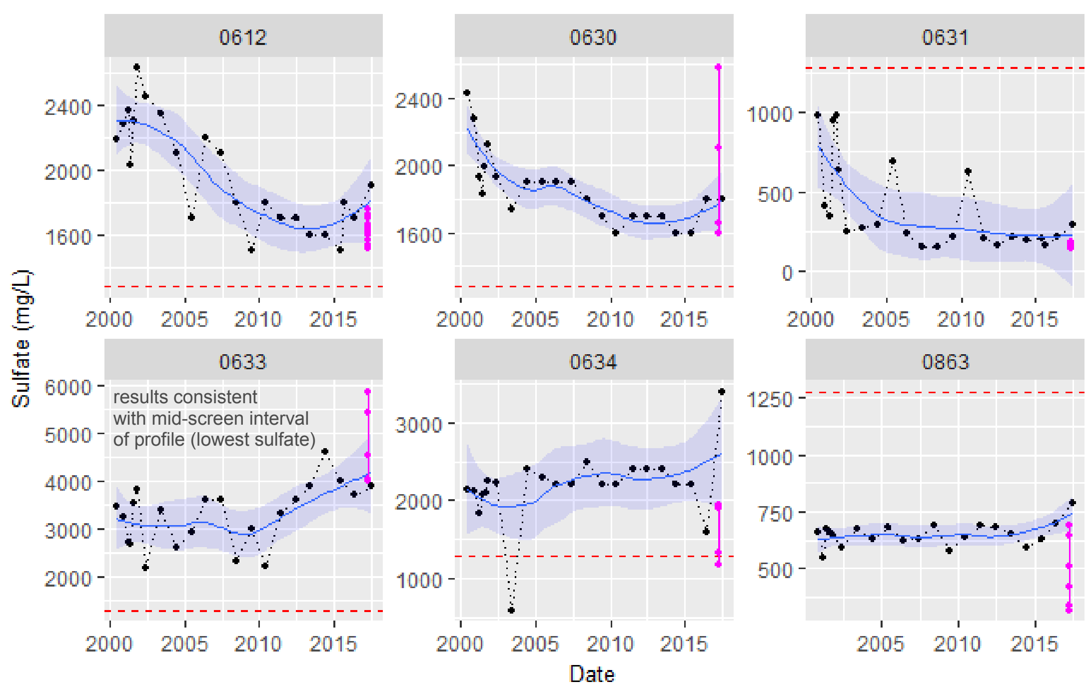
To assess whether the vertical variation observed in some mill tailings area wells might explain historical variation in contaminant concentrations, these data were plotted together in a manner similar to the introductory example in Figure 3b. Figure 22 plots historical annual monitoring results for uranium and sulfate, the primary site contaminants. In contrast to previous figures which used a linear fit, in Figure 22 a smoothed line is added to illustrate the dominant pattern in the data ("loess" smoothing method) (Wickham 2009). This plotting approach is used in several subsequent figures throughout this report.

In Figure 22, corresponding profile results are plotted vertically along the right *y*-axis (–●–). Although contaminant concentrations varied widely in some wells (Figures 13 and 14), this variation does not appear to have influenced routine sampling results. In wells 0612 and 0633, the range of the vertical uranium profile corresponds generally to the confidence interval around the data. However, there is no evidence that it explains the historical trends. Fluctuations in water levels (Figure 23) could also play a role, as could other natural processes. Although the vertical range in well 0630 encompasses the historical range in the data, the increase in uranium concentrations between 2000 and 2002 could be attributable to other factors.

a. Uranium



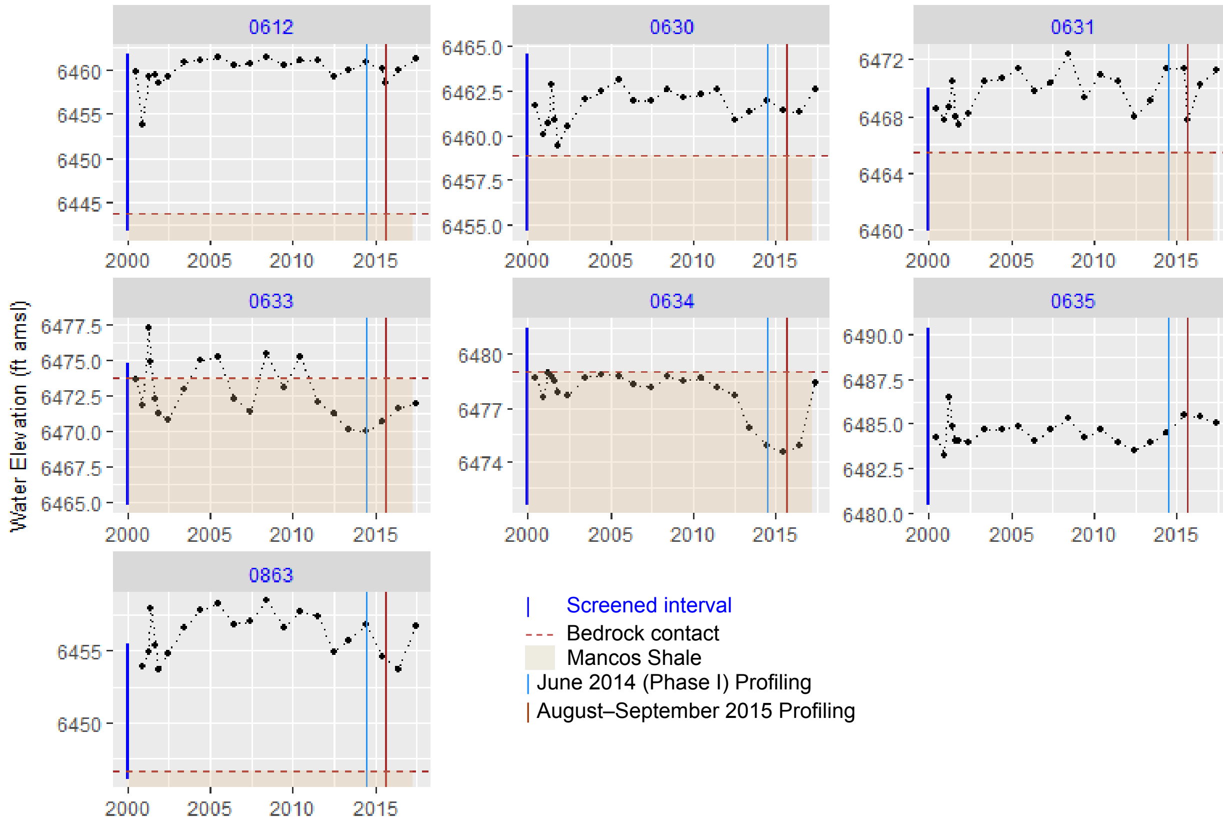
b. Sulfate



Local smoothed regression line and corresponding 95% point-wise CI
Corresponding standard or background level: 0.044 mg/L uranium (MCL); 1276 mg/L sulfate background level
Phase II vertical profile results (right *y*-axis), all from screened interval

Figure 22. Historical Contaminant Versus Vertical Profile Results in Mill Tailings Area Wells

(a) Uranium (background wells and well 0863 with low uranium concentrations excluded); (b) Sulfate (routinely sampled non-background wells)



Note: Hydrographs for wells 0622, 0629, 0632, 0857, 0859, and 0866 are not shown because water elevations are not regularly measured

Abbreviation:
ft amsl = feet above mean sea level

Figure 23. Hydrographs for Mill Tailings Area Wells: 2000–2017

4.2.5 Mill Tailings Area Summary of Findings

Results of the August–September 2015 chemical profiling indicate that the vertical stratification found for SC in both study phases also applies to site contaminants (uranium and sulfate) and most of the major anions (including sulfate) and cations. The most notable variation was measured in wells 0630 and 0631, both of which are routinely monitored and screened in the alluvium and the Mancos Shale. In these wells, uranium concentrations varied by 1 to 2 orders of magnitude within the screened interval, encompassing values both above and below the 0.044 mg/L standard.

In general, no strong correlation was found between uranium concentrations and SC. In contrast to the trends found for SC (increasing with depth), in most mill tailings area wells, uranium concentrations decreased with depth. As such, the use of SC as a surrogate for or indicator of uranium concentrations in mill tailings area wells is not supported. A meaningful correlation was found between sulfate concentrations and SC ($r = 0.94$ for the combined data set evaluated). Groundwater salinity is best explained by sulfate and magnesium in this area of the site.

One factor that may account for the observed variation in both SC and uranium profiles is that many wells are screened in two formations. Within individual wells, groundwater chemistry varies in portions of the well screened in the alluvium versus the Mancos Shale. For example, uranium concentrations are typically higher in the upper screened portion coinciding with the alluvium than in the lower screened portion coinciding with the Mancos Shale. These results suggest that screening wells in several formations introduces uncertainty into the sampling results and data interpretations, especially if the intent is to monitor groundwater conditions in the alluvium.

Other conditions that may account for the variation found in SC and chemical profiles in this area of the site include density-driven flow (which could account for salinity increasing with depth); preferential flow paths (including fracture flow); and stagnant zones in wells, which is indicated in several ^{222}Rn profiles. The extent to which these mechanisms account for the observed variation is beyond the scope of this study.

In most of the mill tailings area wells, the phreatic surface was near or below the alluvium–Mancos Shale contact at the time of profiling. Although not the focus of this study, this is another factor to consider when evaluating sampling objectives and monitoring results. That is, are samples collected from these wells representative of alluvial aquifer conditions at that groundwater elevation or sampling depth? For some wells, this appears to be the case, but for others (e.g., wells 0630 and 0631), it may not.

4.3 Raffinate Ponds Area

SC and chemical profiles from 11 wells in the Durango former raffinate ponds area were obtained in August and September 2015 (Figure 9, Figure 24). Most of these wells are completed in bedrock of the Menefee Formation, which consists of sandstone, siltstone, and some coal layers. A simplified schematic of corresponding well construction information is provided in Figure 25 (screen lengths range 10–40 ft). Two of the wells profiled (0607 and 0598) are screened in different formations.

4.3.1 Hydrogeologic Overview

Groundwater in the former raffinate ponds area occurs in two bedrock units, the Point Lookout Sandstone and the Menefee Formation—both are formations in the Mesaverde Group. The Bodo Fault, a north-northeast striking normal fault, cuts these formations (Figure 24). The fault plane dips to the east-southeast at approximately 55°. Displacement of about 200 ft along the fault has dropped formations down to the east-southeast. The Point Lookout Sandstone is divided into two members: a lower transitional member, consisting of interbedded lenticular sandstones and shales, and an upper massive sandstone member. The Menefee Formation, west of the fault, consists of interbedded massive sandstone and shale along with beds of carbonaceous shale and coal.

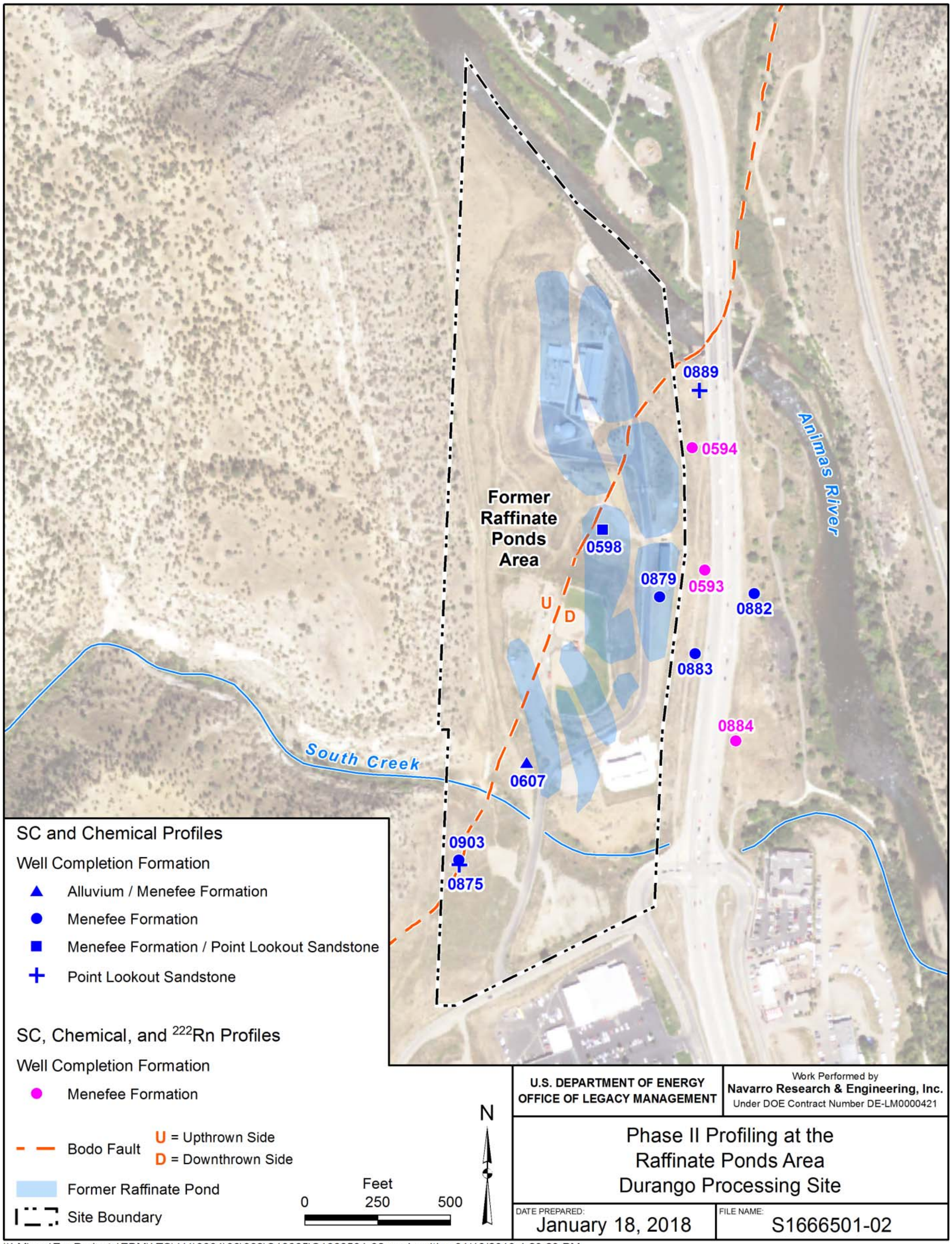


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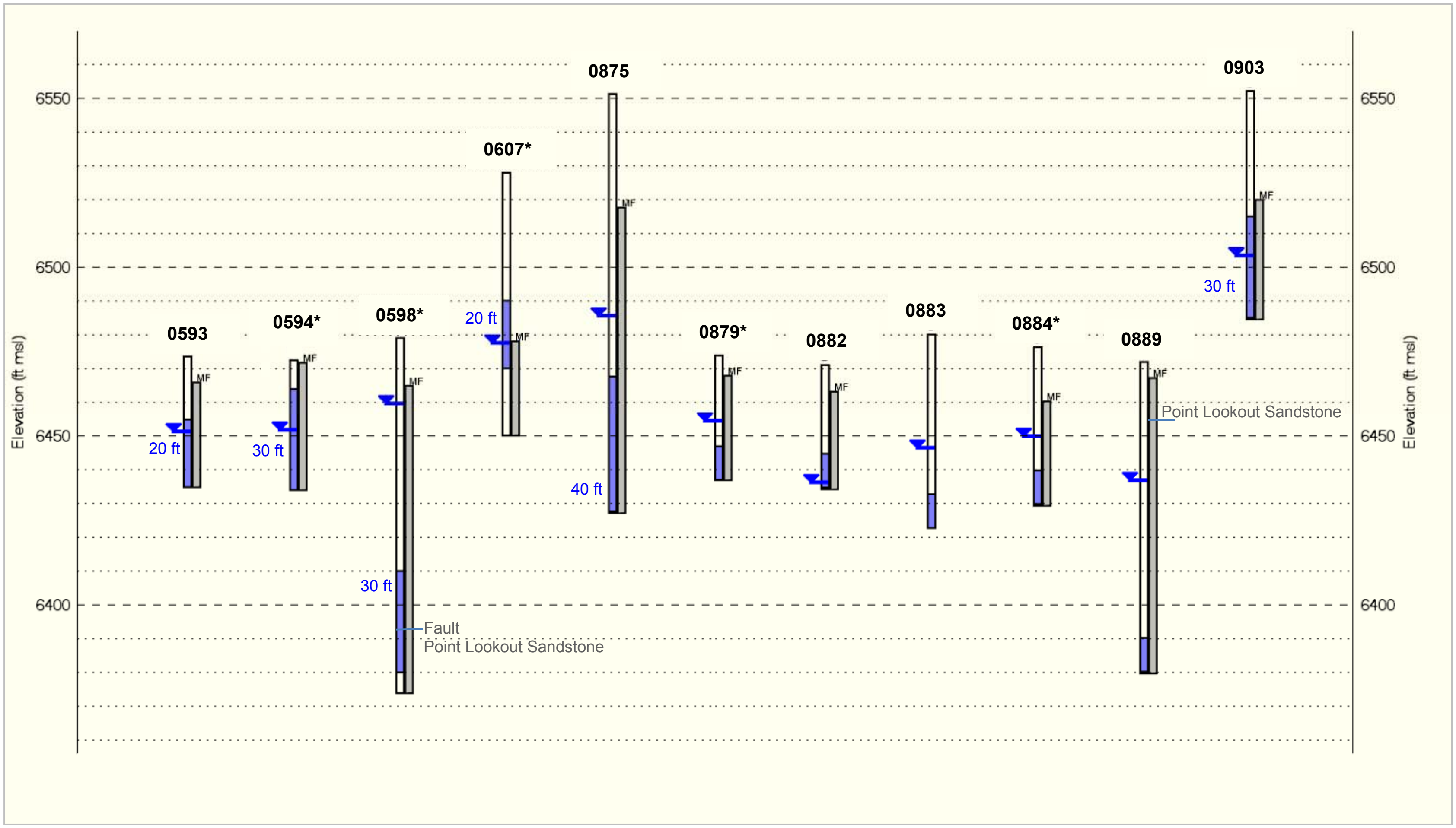
Figure 24. Wells Profiled at the Durango Processing Site Raffinate Ponds Area



Inverted blue triangles show the latest measured groundwater elevations from June 2017 for routinely sampled wells (*) and 2001–2002 for remaining wells.
Black rectangles show the well casings; well screens are shaded blue.
The top of bedrock—the Menefee Formation contact—is shown to the right of well screen.

Notes:
Wells are plotted in order of well ID and, therefore, do not reflect horizontal location. Well screens are 10 ft long except where noted above.
Corresponding well construction logs are available on the LM GEMS website https://gems.lm.doe.gov/#site=DUP.

Abbreviation: MF = Menefee Formation

Figure 25. Well Construction Information for Durango Processing Site Raffinate Pond Area Wells

Groundwater in the raffinate ponds area is assumed to be unconfined (DOE 2002b). It is recharged by infiltration of precipitation and runoff from the Smelter Mountain area and the ephemeral South Creek. Eastward-flowing groundwater also enters the groundwater system near the intersection of Bodo Fault and South Creek. The Menefee Formation consists of mostly low-conductivity sandstone but is relatively permeable where there are fractures or lenticular coal beds. The greatest hydraulic conductivities appear to occur near Bodo Fault and in Menefee Formation coal beds. The Point Lookout Sandstone is the least conductive of the various bedrock units underlying this area of the site. The lower member (predominantly shale and siltstone) of this formation is considered an aquitard (DOE 2002b).

4.3.2 Specific Conductance and Analyte Profile Results

Phase II of this study yielded 168 analyte profiles for former raffinate ponds area wells (11 wells × 15 parameters + 3 ^{222}Rn profiles). Similar to the approach used to present mill tailings area results, this section focuses primarily on results for SC, uranium, and sulfate and on the subset of wells characterized by the greatest degree of stratification or variation within the vertical profiles. Detailed results are provided in Appendix D, which includes all associated data: plotted first by analyte (Appendix D-1) and then by well (Appendix D-2).

Specific Conductance Profiles

Figure 26 plots SC by depth for all 11 former raffinate ponds area wells profiled in August–September 2015. Phase I (June 2014) results are also shown. One well—0598, screened in the Menefee Formation and Point Lookout Sandstone—could not be accessed during Phase I, but was profiled in Phase II. Except for wells 0594 and 0884 (upper casing measurements only), SC profiles obtained in both study phases are similar. The most striking temporal difference was found in well 0594, where SC increased steadily from about 3870 to 5160 µS/cm within the screened interval in the Phase I profile, but was fairly constant in Phase II. Given the well's proximity to the Animas River, this difference might reflect changes in river flow conditions. Based on the SC measurements plotted in Figure 26, two categories of profiles were derived for the former raffinate ponds area wells:

(1) Increasing SC with depth within the screened interval—wells 0593, 0594 (Phase I profile only), 0598, 0875, and 0903.

(2) Fairly constant SC with depth within the screened interval following a marked increase at the casing/screen transition—wells 0883, 0884, and 0889.

The three remaining wells (0607, 0879, and 0882) were not categorized because of insufficient data within the screened interval. In wells 0607 and 0882, most of the water was in the sump at the time of profiling during both phases of this study (Figure 26). In well 0879, a complete SC profile could not be obtained due to an obstruction at about 30.6 ft bgs, just 3 ft into the 10 ft screened interval. Therefore, limited conclusions can be drawn regarding variation in these wells. Table 4 summarizes these observations along with other key well-specific findings for the remaining parameters.

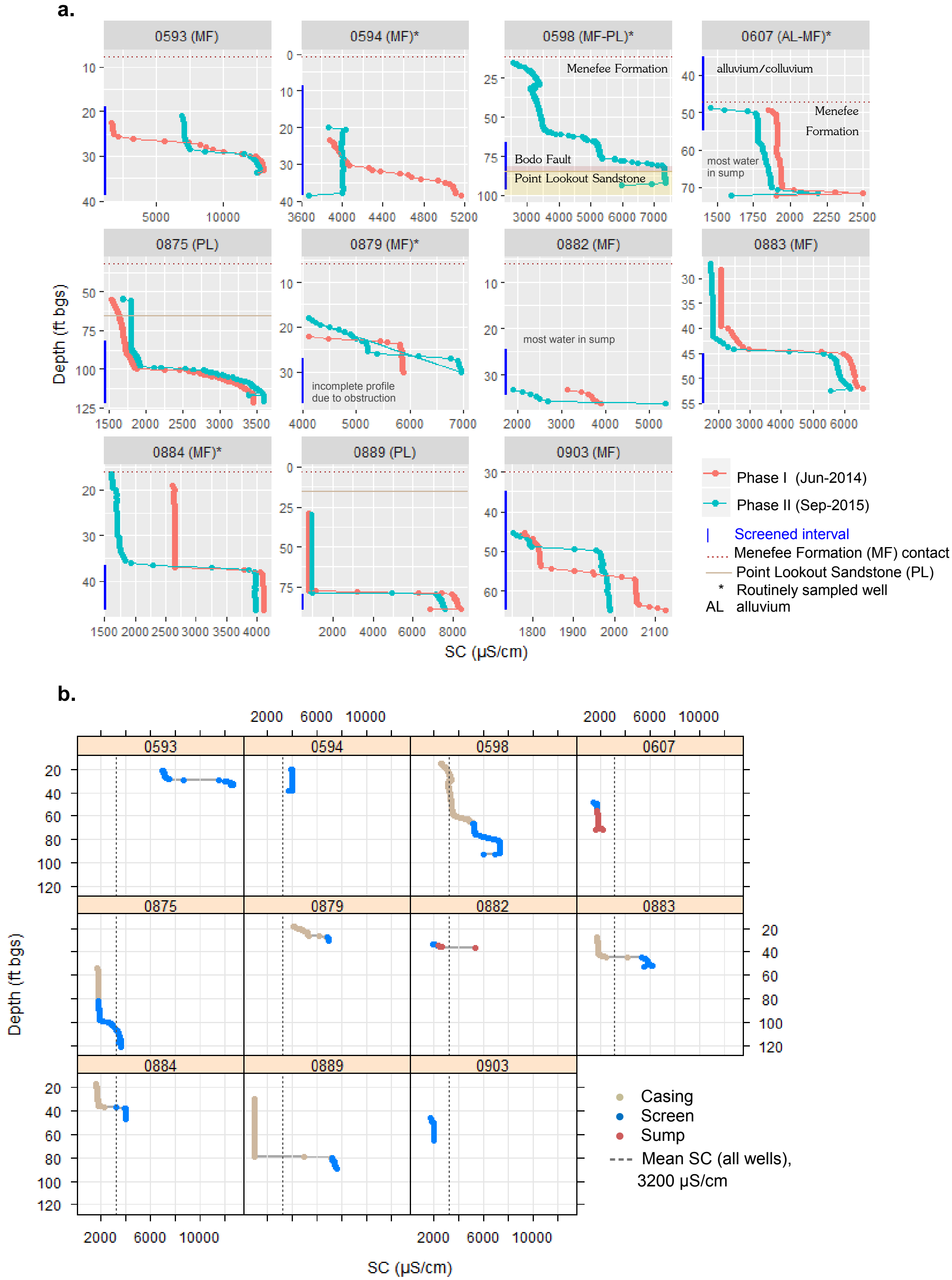


Figure 26. Specific Conductance Profiles in Durango Processing Site Former Raffinate Ponds Area Wells

(a) Phase I and Phase II SC profiles, unique scales and screen intervals shown;
(b) Phase II SC versus depth, common scales

Table 4. Summary of Wells Profiled at the Durango Processing Site Raffinate Ponds Area, Phase II Study

Well	**Zone of Completion**	**Phase I SC CV**[a]	**Phase II Sample *n***[b]	**Comments**
0593	MF	0.61	9[d]	In Phase I, this well had one of the most variable SC profiles at this site based on the CV. Similar, albeit less marked, variation was found in the Phase II profile. Consistent with historical monitoring results (2001–2002), uranium was not detected (<0.001 mg/L) in the vertical profile.
0594[c]	MF	0.11	17[d]	The Phase II SC profile (with little variation) was markedly different from that obtained in Phase I, when SC increased steadily with depth in the screened interval. The ^{222}Rn profile indicates that flow through the well screen may be somewhat restricted.
0598[c]	MF-PL (Bodo Fault)	Not profiled in Phase I	70	This well could not be accessed during Phase I of this study. Chemical profiles were incomplete because the pump could not be advanced beyond approximately 86 ft bgs, which coincides approximately with the Point Lookout Sandstone contact. A subsequent downhole video profile indicated a 2–3 ft discrepancy in screen placement. Although the chemical profile was incomplete, the apparent variation is of interest and discussed further in this section.
0607[c]	AL-MF	0.05	20	At the time of profiling, most of the water was in the sump.
0875	PL	0.33	33	Increasing SC with depth within the screened interval correlating with sulfate and alkalinity profiles. Uranium concentrations were low (<0.001 mg/L). Due to significant drawdown (22.6 ft), the chemical profile results may be suspect.
0879[c]	MF	0.09	13	SC and chemical profiles were incomplete due to an obstruction at about 30.6 ft bgs. Although stratification of SC and other analytes is apparent in measurements or samples from the upper blank casing, within-screen data are insufficient to draw conclusions.
0882	MF	0.07	3	Too few samples to evaluate (*n* = 3). As found for well 0607, most of the water was in the sump.
0883	MF	0.55	19	Although SC increased significantly with depth in both Phase I and Phase II over a range of about 4000 µS/cm, there is very little variation within the screened interval. High DOC and TOC in lowermost sample (120–130 mg/L) possibly attributable to coal bed.
0884[c]	MF	0.22	29[d]	This well is also characterized by a marked change in analyte levels (mostly increases) at the casing/screen transition followed by non-varying (flat) profiles within the screened interval. The ^{222}Rn profile indicates a stagnant zone in the upper casing and high flux within the screened interval.
0889	PL	1.3	41	This well had the greatest degree of stratification in the Phase I profiles based on the CV. Fairly constant SC with depth within screened interval preceded by a marked increase at the casing/screen transition.
0903	MF	0.06	8	In both Phase I and Phase II profiles, SC varies with depth through the screened interval, albeit over a fairly limited range of just several hundred µS/cm (thus the low CV).

Notes:
[a] CV of Phase I SC measurements taken in June 2014 (DOE 2015). In this table, CV values are formatted as follows:
0.67 High (CV ≥ 0.1); 0.06 Mid-Level (0.03 ≤ CV < 0.1).
[b] Number of samples (*n*) collected for chemical analysis (samples were collected at 1 ft intervals).
[c] Well is routinely sampled.
[d] Well was also profiled for ^{222}Rn.

Abbreviations:
AL = alluvium
MF = Menefee Formation
PL = Point Lookout Sandstone

Uranium, Sulfate, and Other Analyte Profiles

Figure 27 plots vertical profile results for all parameters for the former raffinate ponds area wells profiled in Phase II. In this figure, some of the plots are annotated with well labels to facilitate review. As mentioned previously, this data visualization approach is used mainly to help identify the parameters (and wells) with the most widely varying concentrations, as well as those with generally little variation. For example, the variation in vertical profiles for SC, sulfate, and sodium in well 0593 is readily apparent in this figure. Also, uranium concentrations vary widely in wells 0598 and 0884 (Figure 27a). Although pH varies within the neutral range of 7.1 to 8.5, there is no apparent pattern to this variation in any of the wells. For the parameters with the widest ranges in concentrations (SC, uranium, sulfate, and sodium) and those with outlier data (DOC, TOC, and dissolved and total iron), Figure 27b plots the same data using a logarithmic scale to facilitate interpretation. Table 5 summarizes corresponding observations for each parameter or analyte category.

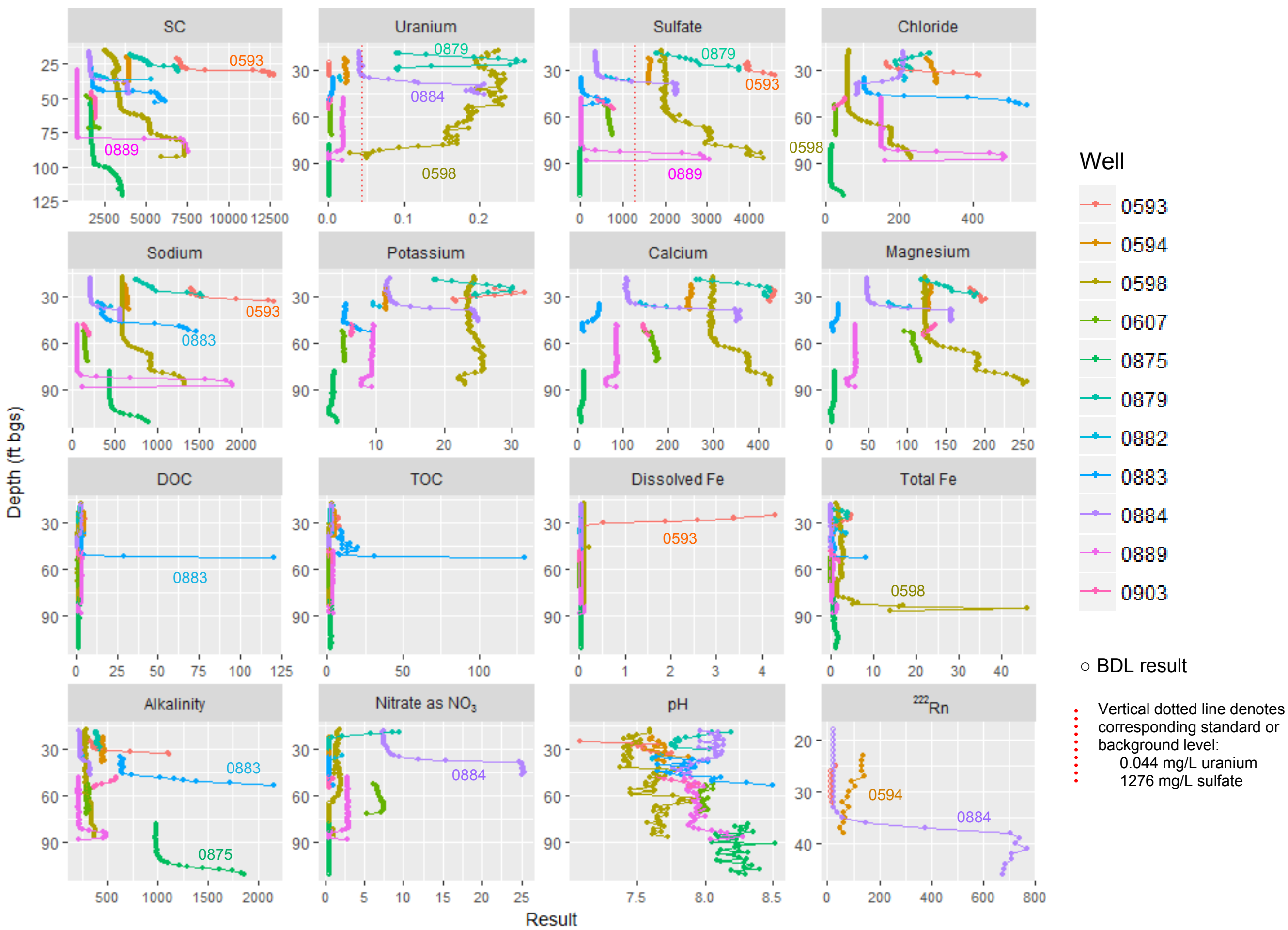
Along with sulfate, concentrations of remaining major ions—in particular alkalinity, sodium, and chloride—vary significantly in some wells. In a number of cases, this variation appears to correlate with the corresponding SC profiles. This finding is most evident for those wells with the most variable SC profiles—for example, wells 0593 and 0884 (Figure 27). (Correlations are examined later in this section.)

High dissolved and total organic carbon concentrations (120 and 130 mg/L, respectively) were measured in the lowermost (52.6 ft depth) sample in well 0883 (Figure 27a). On the basis of the well log, this depth corresponds to the region where a 3 ft coal bed was encountered at 46–49 ft bgs. A corresponding decrease in uranium concentrations was also observed at this depth (Figure 28). No notable variation in DOC or TOC was found in the remaining well profiles (Figure 27b).

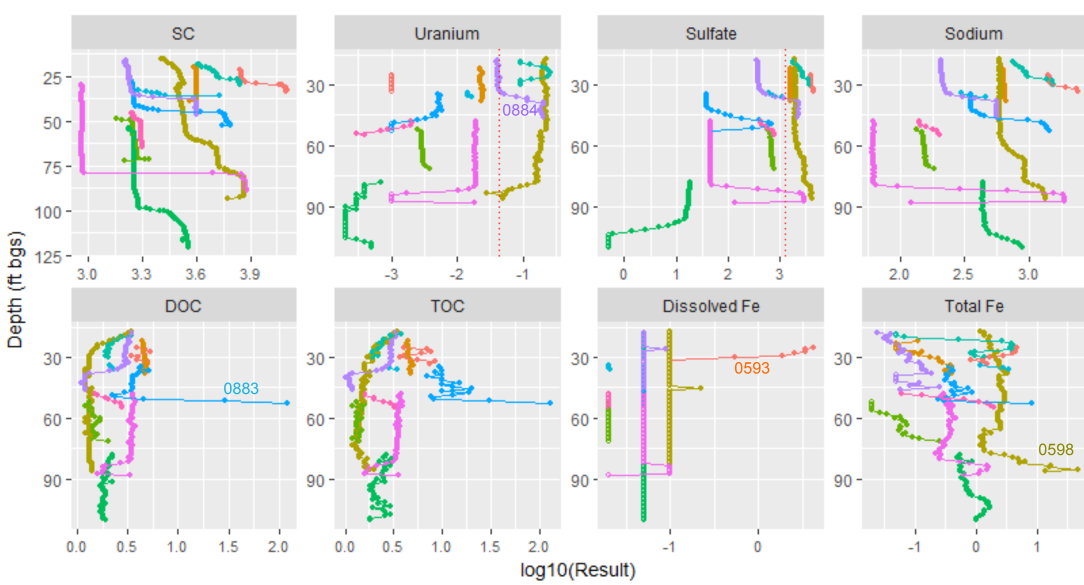
Dissolved iron concentrations were below the detection limit (0.05 mg/L) in 5 of the 11 wells profiled and <0.5 mg/L in most remaining wells. Concentrations as high as 4.3 mg/L were measured in well 0593 (Figure 27a); along with total iron, levels decreased with depth. This may indicate reducing conditions (uranium was not detected in the profile). More variation is apparent in the total iron profiles (Figure 27b, Appendix D-1). Well 0598, in particular, had a notable total iron signature; levels increased from <5 to 46 mg/L within the screened interval. As found for mill tailings area wells, nitrate concentrations were low or below detection limits in most wells profiled (it is not a contaminant at this site).

The remaining discussion focuses on uranium, the primary indicator of milling-related contamination in this area of the site, and sulfate. Although sulfate is not a constituent of concern in the former raffinate ponds area (DOE 2014c), its higher concentrations relative to those of most other major ions may help explain the variation in the SC profiles. To evaluate corresponding groundwater flow dynamics, ^{222}Rn signatures are discussed for the three wells in which profiles were measured.

a. Linear Scale, All Parameters



b. Log Scale: SC, Uranium, Sulfate, Sodium, DOC, TOC, and Dissolved and Total Fe



Note: All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Figure 27. SC and Analyte Profiles for Durango Processing Site Former Raffinate Ponds Area Wells

Table 5. Summary of Observations by Analyte, Former Raffinate Ponds Area Wells

Parameter	General Trends
SC	Except for well 0594, which had an anomalously flat (non-varying) Phase II profile, SC increased with depth in all wells. In some wells, SC increased steadily within the screened interval whereas in others there appears to be a screen effect. In the latter case, SC increases markedly at the transition from the blank casing to the uppermost screened interval. Groundwater is most saline in well 0593, where SC is 6930–12,500 µS/cm in the vertical profile. Except for well 0594, Phase II profile results are generally consistent with those in Phase I.
Uranium	Uranium levels were low, <0.025 mg/L and in most cases <0.005 mg/L, in 8 of the 11 wells profiled. Uranium was detected above the 0.044 mg/L 40 CFR 192 standard in three wells: 0598, 0879, and 0884. All of these wells are screened in the Menefee Formation. Well 0598 is also screened in the Point Lookout Sandstone, which is separated from the overlying Menefee Formation by the Bodo Fault zone. Chemical profiling of wells 0598 and 0879 could not be completed due to obstructions encountered during sampling. Nonetheless, the variation in the uranium profile well 0598 was marked enough within the screened interval to warrant further discussion. Marked variation in uranium concentrations was also found in well 0884.
Sulfate	Another indicator of site-related contamination (DOE 2014c) and also one of the major ions contributing to the salinity or SC profiles due to higher concentrations. In most cases, sulfate concentrations vary with depth, consistent with trends observed for SC.
^{222}Rn	Radon-222 was determined in three wells screened in the Menefee Formation: 0593, 0594, and 0884. Low concentrations in wells 0593 and 0594 indicate potential restricted flow in these wells. Results for well 0884 suggest that the Menefee Formation contains groundwater with ^{222}Rn concentrations exceeding 700 pCi/L.
Remaining major ions	The greatest degree of variation was found in the sodium, sulfate, chloride, and alkalinity profiles. Overall (based on the combined data set), the sodium profiles best explained the variation in SC.
Nitrate as NO_3	Nitrate was BDL, which is 0.5 mg/L, in 2 of the 11 wells profiled and <10 mg/L in most remaining wells. These profiles were generally flat (i.e., non-varying). Well 0884 is an exception, where the variation in the nitrate profile is similar to that observed for SC and other parameters.
DOC and TOC	High DOC and TOC (120–130 mg/L) measured in the bottom sample within the screened interval (52.6 ft bgs) in well 0883 correspond to a coal bed region. No notable variation in DOC or TOC was found in the remaining well profiles.
Iron, total and dissolved	Dissolved iron results were BDL (0.05 mg/L) in 5 of the 11 wells profiled and <0.5 mg/L in most remaining wells. Well 0593 had the highest dissolved iron concentrations (0.83–4.7 mg/L), which reduced gradually with depth in the screened interval. More variation is apparent in the total iron profiles as shown in Appendix D-1, but total iron levels do not appear to correlate with other analytes.
pH	pH varies within the neutral range of 7.1–8.5.

Note:
Detailed plots of profile results are provided in Appendix D-1 for each of the 16 individual analytes.

Figure 28 plots uranium concentrations by depth in former raffinate ponds area wells. Uranium levels were low (below the 40 CFR 192 standard) in 8 of the 11 wells profiled (<0.025 mg/L and in most cases <0.005 mg/L). Although some vertical variation is apparent in these profiles, it is on a very small scale and negligible relative to that found in other profiles in this study. Six of these eight wells are no longer sampled, perhaps because of the historically low uranium concentrations measured during site characterization activities in 2001–2002 (DOE 2002b).

As shown in Figure 28, uranium concentrations exceed the 0.044 mg/L 40 CFR 192 standard in three of the wells profiled: 0598, 0879, and 0884. Wells 0598 and 0879 coincide with locations of the former raffinate ponds, whereas well 0884 is located offsite about 300 ft west of the Animas River, hydraulically downgradient of the ponds (Figure 24). All three of these wells are sampled annually, usually in June of each year, coinciding with high Animas River flows. Only a few samples could be collected from the screened interval of well 0879, so little can be concluded about variation in this well. Although it was also not possible to obtain a full vertical chemical profile in well 0598 (in which there was an obstruction at the mid-screen interval), it was possible to obtain a full SC profile (Figure 26) (the SC sonde has a relatively small diameter).

Site records indicate that wells 0598 and 0884 have been likely sampled consistently at the mid-screen interval. However, theoretically, the range in uranium concentrations measured in both these wells is potentially great enough to impact interpretations of temporal trends. This conclusion applies in particular to well 0598, where uranium concentrations span nearly an order of magnitude—decreasing from 0.19 to 0.028 mg/L—within the screened interval. The extent of this variation is not fully known because the lowermost 10 ft of the 30 ft screened interval could not be sampled.[10] Nonetheless, these results highlight the potential problems associated with screening wells in multiple formations, as discussed below.

The upper portion of the well screen in well 0598 is in the Menefee Formation, characterized by higher uranium concentrations, about 0.1–0.2 mg/L based on the vertical profile. The screen then intersects the Bodo Fault zone, which separates the Menefee Formation from the underlying Point Lookout Sandstone, coinciding with the bottom 11.5 ft of the screen. In the fault region, uranium concentrations decrease progressively to about 0.05 mg/L. Site wells screened solely in the Point Lookout Sandstone were monitored for a limited period, 1993–2002. During that time, uranium concentrations ranged from 0.0001–0.03 mg/L (with an average of 0.004 mg/L). Depending on the depth at which well 0598 is sampled, it is possible that sampling results reflect either water from the Menefee Formation or a mix of Menefee Formation water with groundwater from the Point Lookout Sandstone. Further interpretation is not possible until the obstruction is cleared and the SC and analyte profiles, with the addition of ^{222}Rn, can be repeated.

Consistent with the second general category of profiles defined previously, in well 0884, uranium concentrations are fairly constant (and low) throughout the upper casing but then begin to increase at the casing/screen transition. In the upper 3 ft of the 10 ft screened interval, concentrations double (from 0.11 to 0.2 mg/L) but then stabilize.

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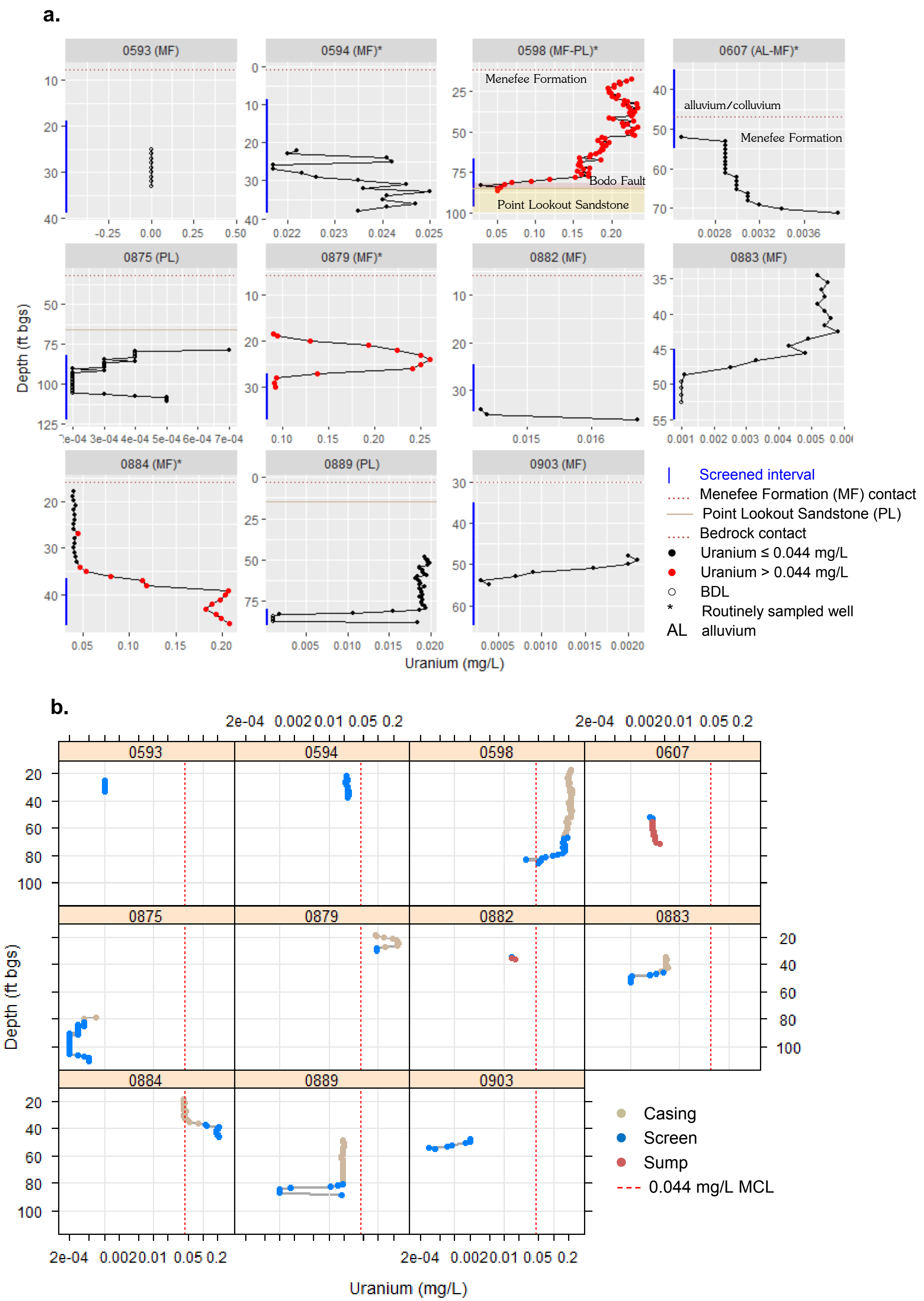
[10] A subsequent downhole video taken in July 2016 indicated a 2–3 ft discrepancy in screen placement. The top of the screen was 2 ft higher than that indicated in the well log and the screen bottom was 3 ft higher (Appendix B). The well was found to be clean (i.e., no obstruction of the visual field). Although not conclusive, it is possible that more of the screened interval was characterized than indicated in Figure 28.



Note: Chemical profiles for wells 0598, 0875, and 0879 were incomplete due to obstructions encountered during sampling.

Figure 28. Uranium Profiles in Durango Processing Site Former Raffinate Ponds Area Wells (a) August–September 2015 profiles, unique scales and screen intervals shown; (b) Uranium versus depth, common scales

Figure 29 plots corresponding results for sulfate, a major ion and common milling-related contaminant. This parameter is not monitored in the former raffinate ponds area wells, given magnitudes considered similar to background concentrations (DOE 2014c). In most cases, sulfate concentrations increase with depth similar to SC profiles. Exceptions are Point Lookout Sandstone well 0875, with very low concentrations (<20 mg/L) and a decreasing trend with depth.

To examine potential factors accounting for the trends discussed above, in particular those found for uranium, Figure 30 and Figure 31 plot all analyte profiles for wells 0598 and 0884. These data also represent the two types of profile categories described previously:

(1) Gradual increases in SC and most major anions and cations within the screened interval (well 0598).

(2) Variation within the profile characterized by a marked increase at the casing/screen transition (well 0884).

As shown in Figure 28, wells 0598 and 0884 are the only two former raffinate ponds area wells with both elevated uranium concentrations (>0.044 mg/L) and sufficient data within the screened interval to evaluate. Also, both wells are routinely monitored, allowing comparisons of vertical profile results with the historical record (discussed in Section 4.3.4).

In well 0598, the increase in SC and sulfate concentrations with depth within the Menefee Formation–Bodo Fault zone–Point Lookout Sandstone transition zone applies to all major ions except potassium. Dissolved iron was generally below detection limits, but total iron concentrations increased markedly—from 1 mg/L to 46 mg/L—in the mid-screen region coinciding with the Bodo Fault zone. Uranium concentrations decrease with depth in a manner inversely proportional to trends for the major ions. It is possible that uranium is being sorbed to ferric precipitates in the lower portion of the well. Potassium levels also decreased within the screened interval but over a small range (3–4 mg/L). Both DOC and TOC were elevated in the upper casing relative to screen interval measurements (Figure 30).

In well 0884, screened solely in the Menefee Formation, vertical profiles for most parameters (including uranium) mirror the SC profile (Figure 31). Concentrations are uniformly low in the upper casing and then increase markedly at the casing/screen transition. This is even true for nitrate, an analyte with no pattern or vertical trend in all other Durango processing site wells. Perhaps most notable is the marked increase in ^{222}Rn at the screen onset, from <21 mg/L (BDL) to as high as 767 pCi/L. These results are discussed along with remaining ^{222}Rn profiles at the conclusion of this section. As with well 0598, DOC and TOC were higher in the upper casing and decreased to uniformly low levels (1.2 mg/L) within the screened interval.

Full profiles for all remaining former raffinate ponds area wells are provided in Appendix D-2. Profiles shown for wells 0598 and 0884 (Figure 30 and Figure 31) illustrate the types and degree of variation in analyte concentrations that can be found in a monitoring well. In the first case, the range in parameter concentrations (including uranium) within the screened interval was large enough to affect interpretations if sample depths are not known or consistent. In the second case (well 0884), most results were fairly homogenous within the screen. Although the former would have greater implications, both situations highlight the need for accurate documentation regarding screen and sample depths.

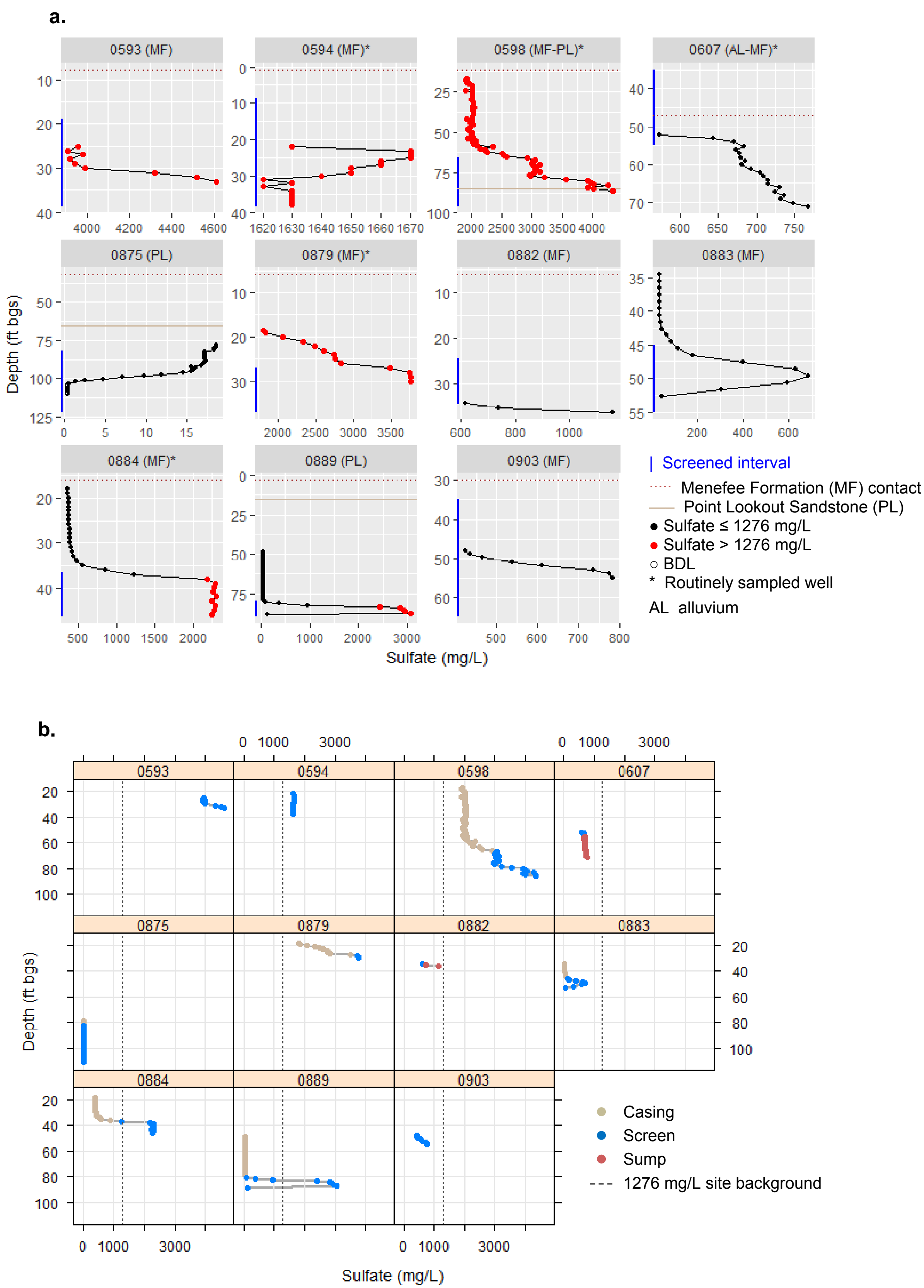
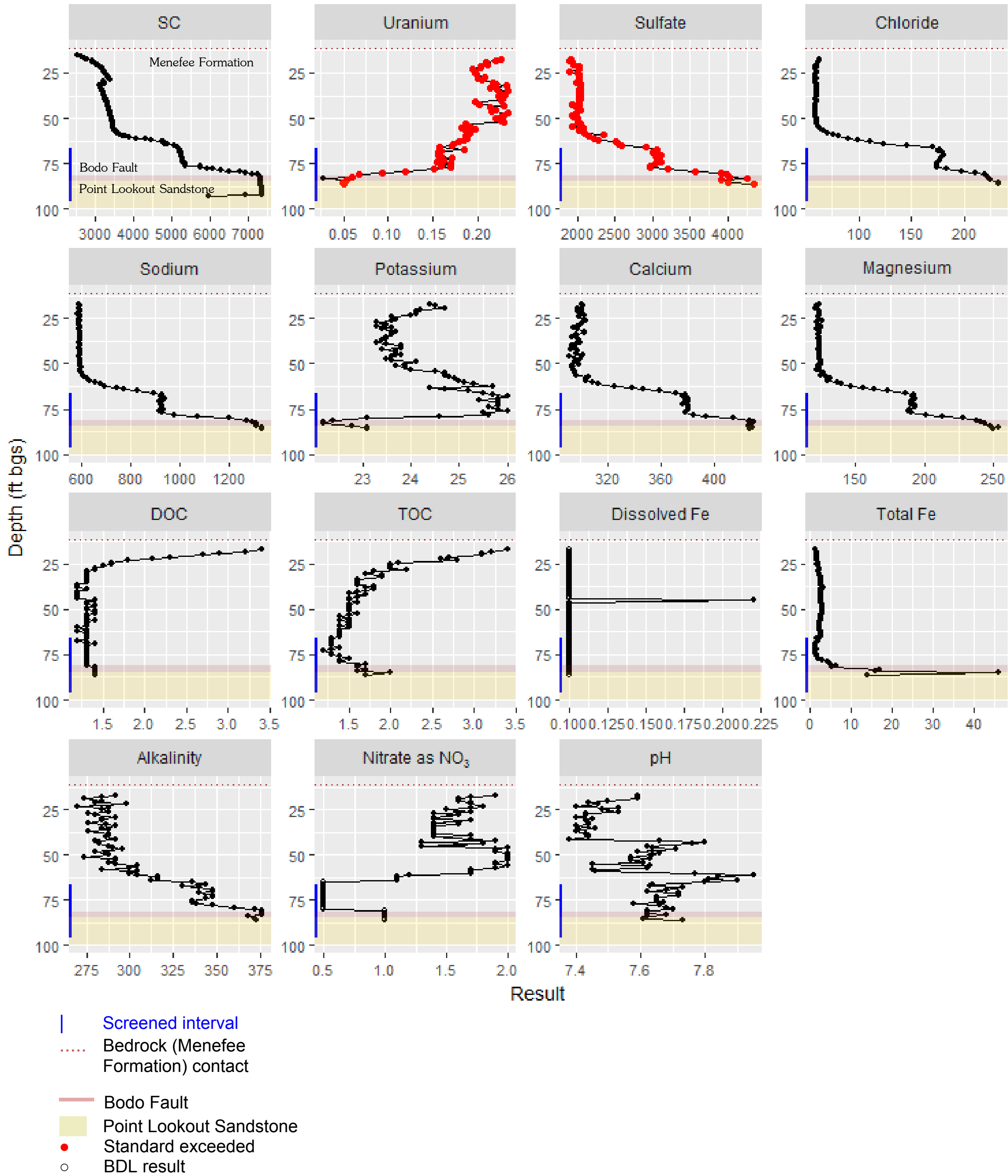


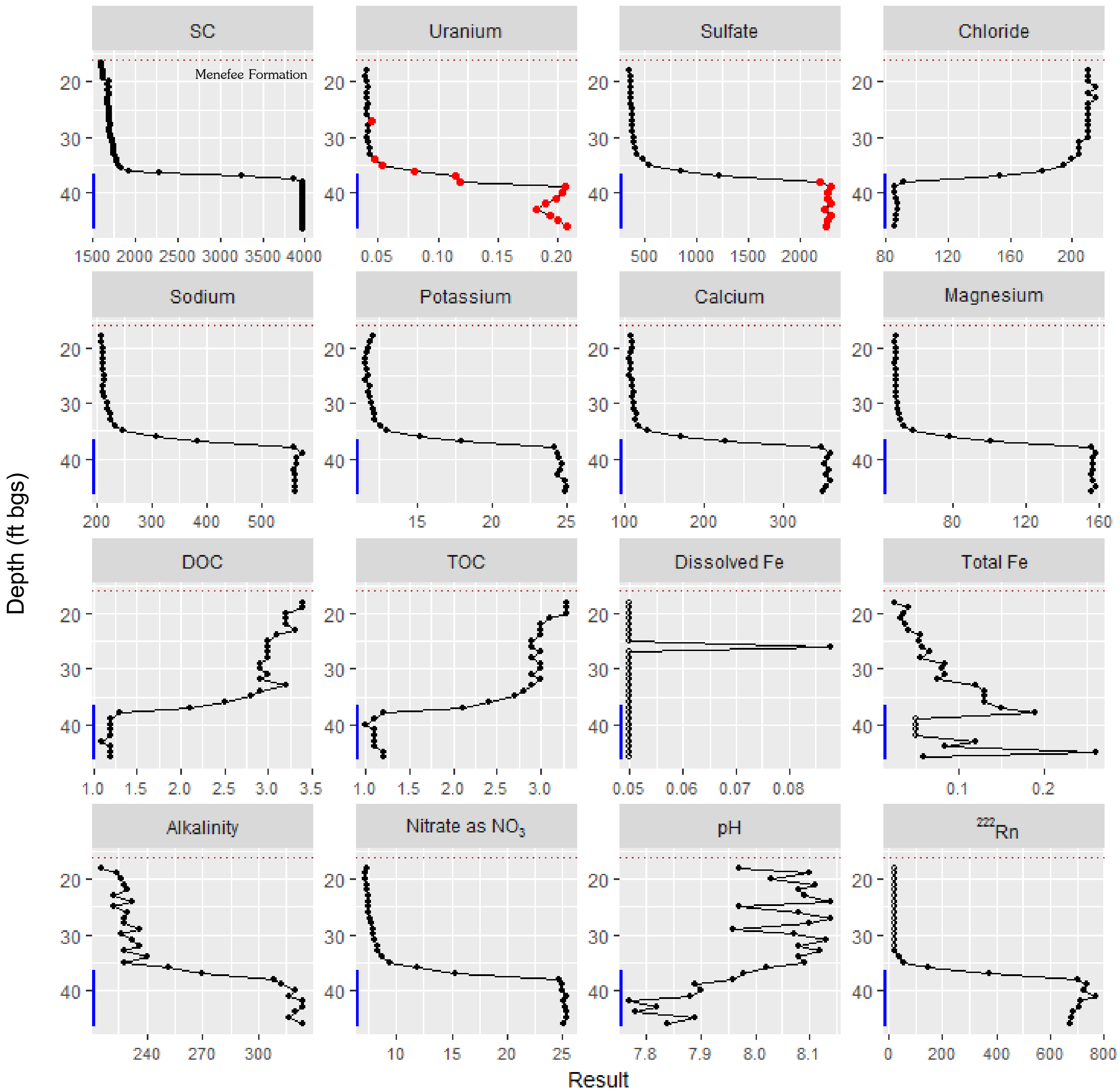
Figure 29. Sulfate Profiles in Durango Processing Site Former Raffinate Ponds Area Wells

(a) August–September 2015 profiles, unique scales and screen intervals shown;
(b) Sulfate versus depth, common scales



Notes:
All units in mg/L except SC (µS/cm) and pH.
Alkalinity is measured as $CaCO_3$.
Exceeded standards are either UMTRCA maximum contaminant limit (MCL) or site standard (DOE 2014c). The established limits are 0.044 mg/L uranium, 1276 mg/L sulfate (which is background), and 44 mg/L nitrate as NO_3.
Chemical profiles are incomplete because the pump could not be advanced beyond approximately 86 ft bgs, which coincides with the region of the Point Lookout Sandstone contact.

Figure 30. Variable Profiles from Former Raffinate Ponds Area Well 0598, August 2015



| Screened interval

····· Bedrock (Menefee Formation) contact

● Result exceeding corresponding UMTRCA MCL or site standard (DOE 2014c)
0.044 mg/L uranium, 1276 mg/L sulfate; 44 mg/L nitrate as NO_3

○ BDL result

Notes:
All units in mg/L except SC (µS/cm), alkalinity (mg/L as $CaCO_3$), pH, and ^{222}Rn (pCi/L).

Figure 31. Variable Profiles from Former Raffinate Ponds Area Well 0884, August 2015

Radon-222 Profiles

Radon-222 concentrations were analyzed in samples collected on September 24, 2015, from three former raffinate ponds area wells: 0593, 0594, and 0884. All three wells are completed in bedrock of the Menefee Formation. Corresponding ^{222}Rn profiles are shown in Figure 32.

Well 0593 had low ^{222}Rn concentrations (7.7–30.0 pCi/L) throughout the profile; results were below the 14 pCi/L detection limit in the mid-screen portion (this well is not routinely monitored).

Well 0594 had ^{222}Rn concentrations as high as 143 pCi/L, but overall levels were low relative to those measured in well 0884, which exceeded 700 pCi/L. Corresponding analyte profiles in well 0594 had no distinct pattern (Appendix D). In both Phase I (June 2014) and Phase II (August–September 2015), the water level in this well was at the mid-screen interval at the time of profiling. As discussed later, uranium concentrations have fluctuated from about 0.02 to 0.19 mg/L (below and above the 0.044 mg/L standard).

In both wells 0593 and 0594, the water level at the time of sampling was below the casing/screen contact (Figure 32). This factor limits what conclusions can be drawn regarding the ^{222}Rn profiles in these wells. However, the low ^{222}Rn concentrations relative to those measured in well 0884 (discussed below) appear to indicate low groundwater flux rates within the Menefee Formation in the regions where the wells are screened.

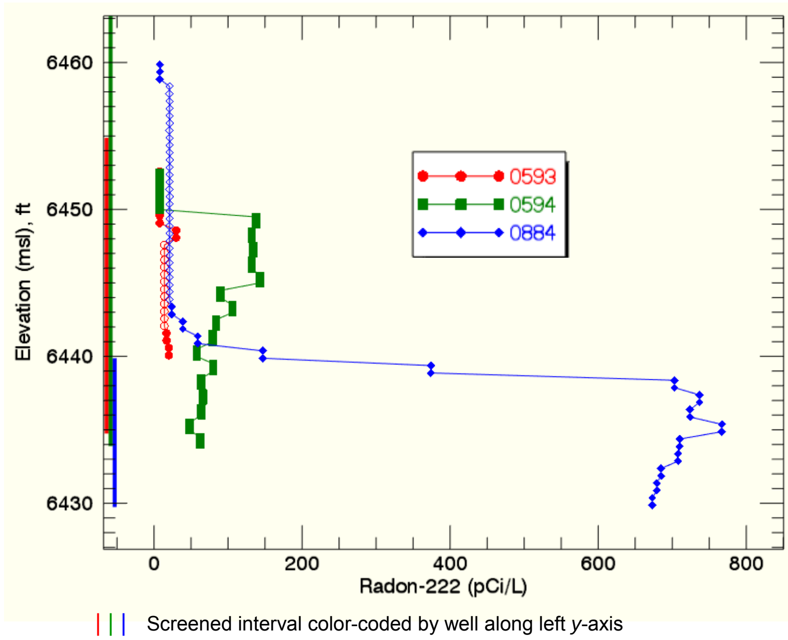
The ^{222}Rn concentration profile from well 0884 shows the expected relationship of groundwater flowing through the well screen (high flux rate as indicated by ^{222}Rn > 700 pCi/L) and a stagnant zone in the upper casing (most results were BDL [<21 pCi/L]).

4.3.3 Assessment of Correlations: Pairwise Comparisons

Consistent with the approach used for the mill tailings area, scatterplot matrices were generated to visualize the pairwise relationships among the 15–16 variables measured during the Phase II study for former raffinate ponds area wells. Because of the significant drawdown in wells screened in the Point Lookout Sandstone (and also very low uranium concentrations), this analysis focuses on results for wells screened solely in the Menefee Formation. Figure 33 illustrates these relationships using the combined data set for the following seven wells: 0593, 0594, 0607, 0882, 0883, 0884, 0903.

To simplify the presentation, three variables were excluded from the analysis: dissolved iron, nitrate (as NO_3), and ^{222}Rn. Dissolved iron was excluded because, as was found for mill tailings area wells, most results were BDL. In most wells, nitrate levels were low; it is not a constituent that is monitored at the site. Radon-222 was excluded because it was detected in only 3 of the 11 raffinate ponds area wells profiled.

a. 222Rn Profiles, Common Scale



b. 222Rn Profiles, Unique Scales

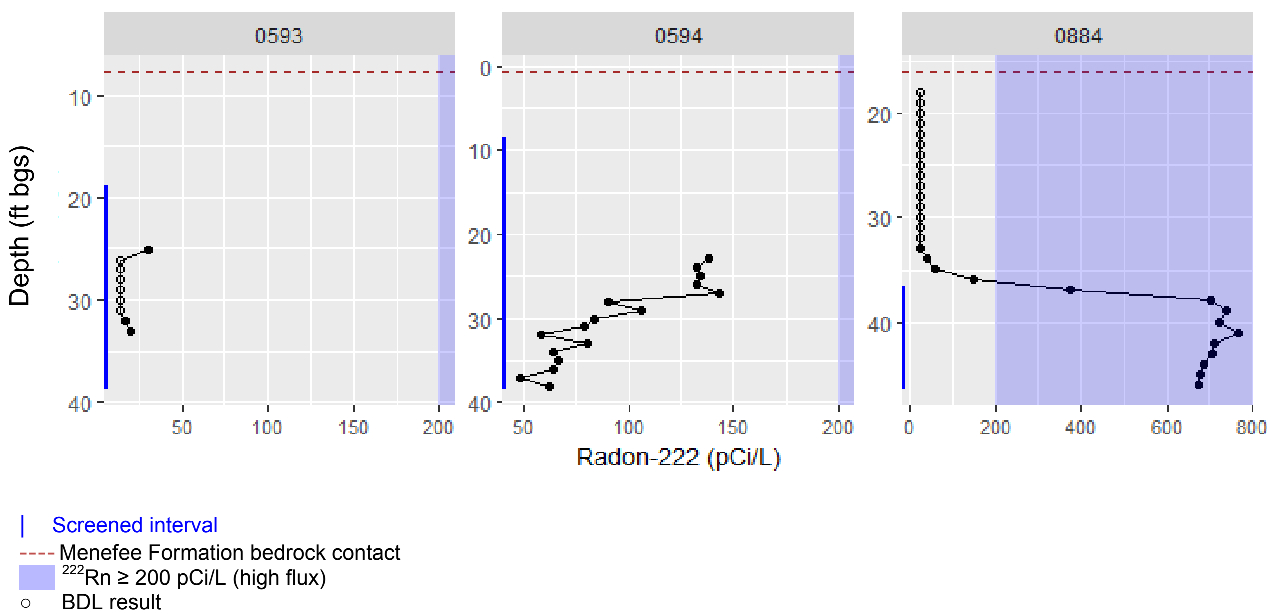
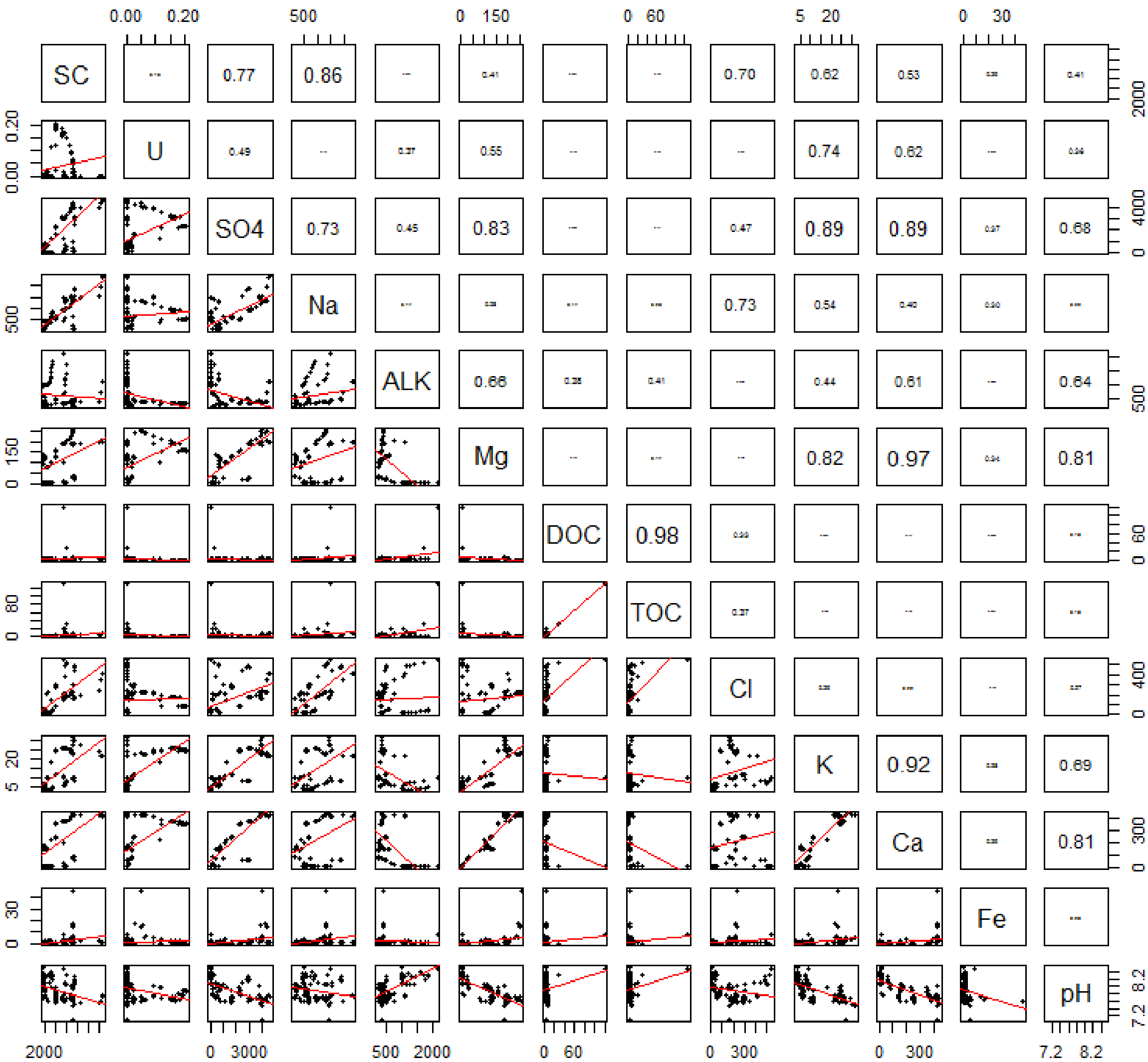


Figure 32. Radon-222 Profiles in Former Raffinate Ponds Area Wells



0.86 Absolute value of Pearson's product-moment correlation coefficient (*r*). Font size proportional to magnitude of *r*.
Upper-right triangle: Corresponding correlation coefficients for each variable pair.
Lower-left triangle: pairwise scatterplots, where — is linear trend line.

Notes:
Scatterplot generated using the **pairs()** function from *R*'s base graphics, *R* version 3.4.2 (R Core Team 2017). Although this matrix shows the linear trendline for each pairwise combination, in many cases, the relationships are *not* linear.
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.
Scales shown on *x*- and *y*-axes of figure.

Abbreviations:
U = uranium; SO4 = sulfate; Na = sodium; ALK = alkalinity; Mg = magnesium; Cl = chloride; K = potassium; Ca = calcium

Figure 33. Scatterplot Matrix of Key Variables, Former Raffinate Ponds Area Well Subset Combined Data Set for Wells Screened Solely in the Menefee Formation: 0593, 0594, 0607, 0882, 0883, 0884, 0903, Screened Interval Only

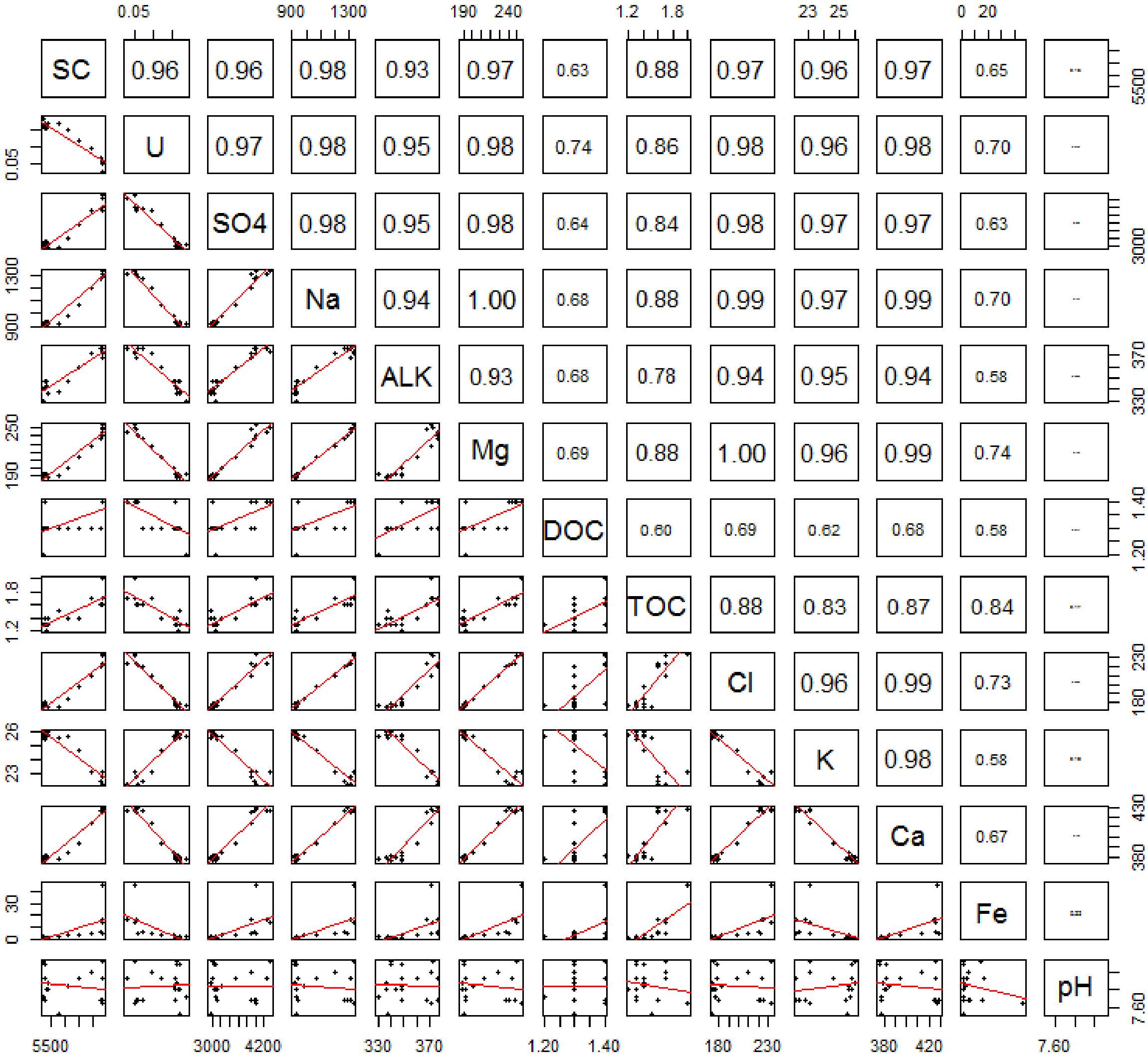
As shown in Figure 33, the SC signatures for this combined data set are best correlated with sodium ($r = 0.86$) and to a lesser extent sulfate ($r = 0.77$). Variable combinations that appear to be correlated with little scatter about the regression line (i.e., a fairly strong linear relationship) include:

- Magnesium and calcium, $r = 0.97$
- Potassium and calcium, $r = 0.92$
- DOC and TOC, $r = 0.98$

There is no linear relationship between SC and uranium ($r = 0.18$, not discernible in Figure 33). Of all the variables, uranium is most correlated with potassium ($r = 0.74$), but the correlation is not strong, as indicated by the data scatter about the regression line. A similar relationship between uranium and potassium was also found for the mill tailings area well subset ($r = 0.86$; Figure 18). For raffinate ponds area wells, the overall lack of agreement between uranium and many parameters might simply reflect the very low uranium concentrations measured in most of these wells.

Figure 34 shows the scatterplot matrix for well 0598, screened in both the Menefee Formation and the Point Lookout Sandstone. This well had some of the highest uranium concentrations at this site. Except for iron, pH, and organic carbon (DOC and TOC), there are strong correlations ($r \geq 0.93$) between most variable pairs, for example, between SC and most major ions. Similarly strong, but negative, associations are apparent between uranium and SC ($r = -0.96$, $r^2 = 0.92$), as well as between uranium and most major ions ($-0.98 \leq r \leq -0.95$). As found for the data subset representing wells screened in the Menefee Formation, uranium is positively—and in this case strongly—associated with potassium ($r = 0.96$). These strong linear relationships are evidenced by the lack of scatter in most of the pairwise plots shown in the lower-left triangle of Figure 34.

Figure 35 plots SC versus uranium for all former raffinate ponds area wells based on the Phase II vertical profiles. Only data from the screened interval were used. Except for well 0598 (discussed above), there is no strong linear relationship between SC and uranium. For the seven remaining profiles, correlations were mostly weak ($r^2 = 0.10$–0.47). A similar plot was generated using historical monitoring results for the five wells that are routinely monitored (Figure 36). Correlations were also weak using this data set ($r^2 = 0.012$–0.37), even for well 0598 ($r^2 = 0.36$). The latter finding contradicts correlation results based on the corresponding vertical profile for well 0598 (Figure 35), which indicated a fairly strong inverse correlation between SC and uranium ($r^2 = 0.92$).

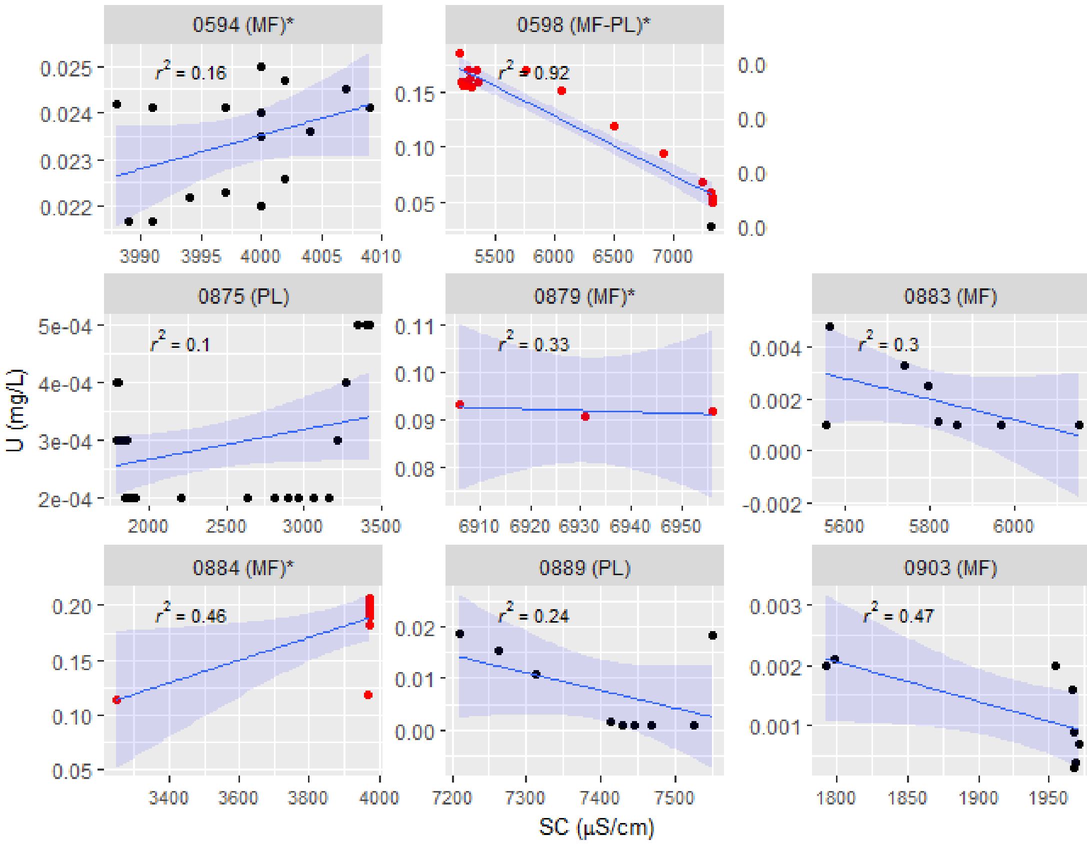


0.96 Absolute value of Pearson's product-moment correlation coefficient (*r*). Font size proportional to magnitude of *r*.
Upper-right triangle: Corresponding correlation coefficients for each variable pair.
Lower-left triangle: pairwise scatterplots, where — is linear trend line.

Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.
Scatterplot generated using the **pairs()** function from *R*'s base graphics, *R* version 3.4.2 (R Core Team 2017).
Scales shown on *x*- and *y*-axes of figure.
Although this matrix shows the linear trendline for each pairwise combination, in many cases, the relationships are *not* linear.

Abbreviations:
U = uranium; SO4 = sulfate; Na = sodium; ALK = alkalinity; Mg = magnesium; Cl = chloride; K = potassium; Ca = calcium

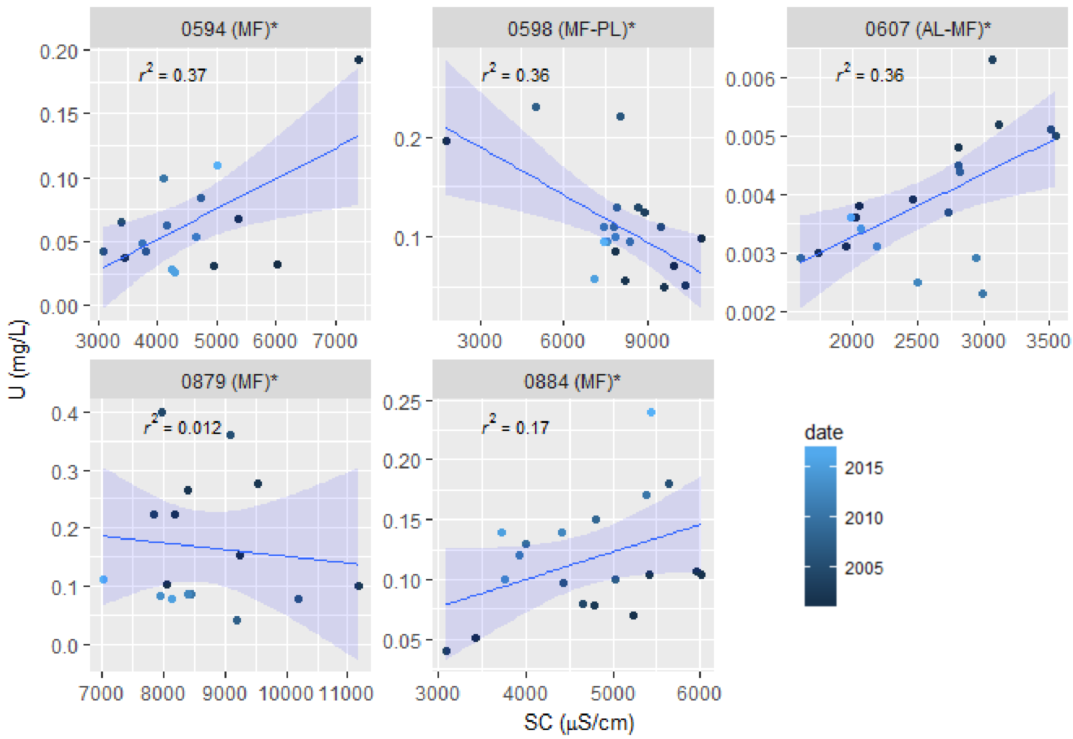
Figure 34. Scatterplot Matrix for Former Raffinate Ponds Area Well 0598



Linear regression line and corresponding 95% point-wise CI
● Red points denote uranium concentrations > 0.044 mg/L 40 CFR 192 MCL
r^2 = coefficient of determination
* denotes wells that are routinely sampled

Notes:
Well 0593 is not shown, as uranium has not been detected in this well, as found in the vertical profile.
Wells 0607 and 0882 are not shown, given the limited data from the screened interval (most results from sump).

Figure 35. SC vs. Uranium in Durango Site Raffinate Ponds Area Phase II Vertical Profiles Screened Interval Only



Linear regression line and corresponding 95% point-wise CI
• Color of points denotes relative date; darker points are older, whereas lighter points are more recent.
r^2 = coefficient of determination

Note:
Routine monitoring usually occurs annually, in June.

Figure 36. SC Versus Uranium in Raffinate Ponds Area Wells Based on Routine Sampling, 2000–2017

4.3.4 Routine Monitoring Results Versus Vertical Profiles

To assess whether the vertical variation observed in former raffinate ponds area wells might explain historical variation in contaminant concentrations, Figure 37 plots historical annual monitoring results for uranium, the primary site contaminant. Corresponding vertical profile results are plotted vertically along the right *y*-axis. Points are color-coded to denote the corresponding portion of the well: • (upper casing); —•— (screen); and • (sump). For wells 0594, 0607, and 0879, uranium concentrations in samples collected from within the screened interval are lower than most historical results. Note that the phreatic surface in well 0607 was in the lowermost portion of the screened interval during both profiling events, June 2014 (high water) and August 2015.

For well 0598, screened in the Menefee and Point Lookout Sandstone formations, the range in uranium concentrations measured within the screened interval in August 2015 (Figure 28) encompasses most of the historical results since 2000. For well 0884, the variation in the vertical profile generally corresponds to the confidence interval band shown in Figure 37. But this variation probably doesn't explain the apparent increasing trend in uranium concentrations in the last several years. Well 0884 is located about 300 ft west of the Animas River (Figure 24); water levels have increased on average about 5 ft over the 17-year period reflected in Figure 37.

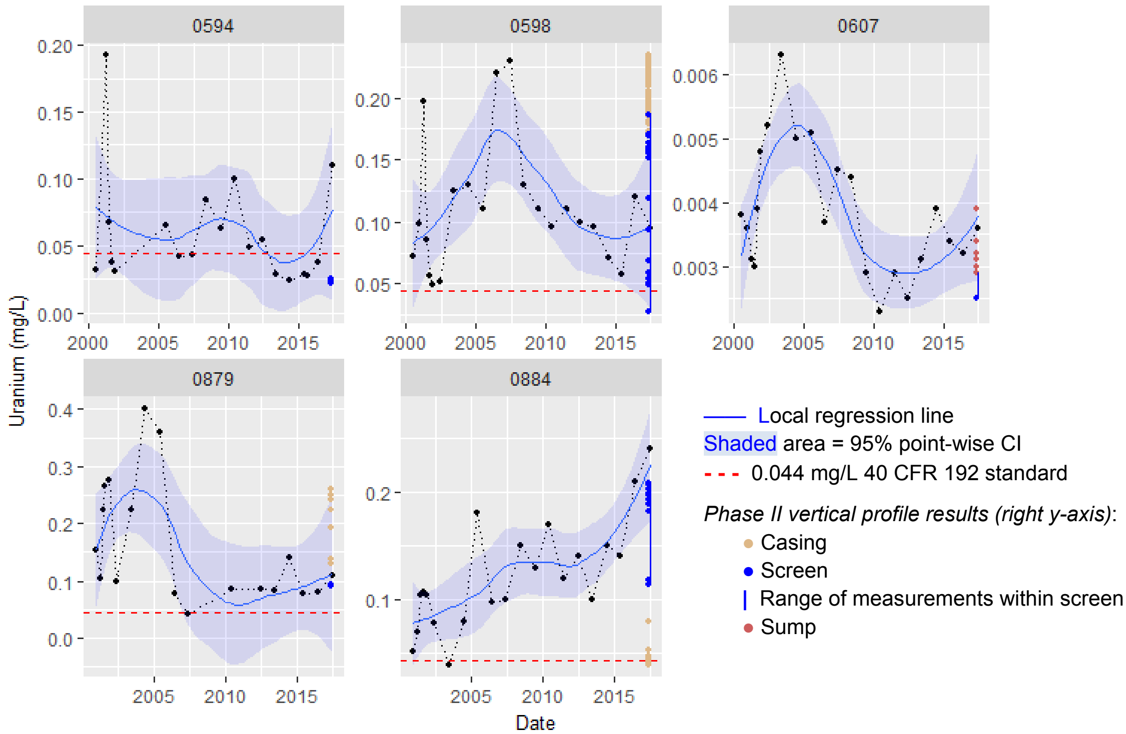


Figure 37. Historical Uranium Concentrations Versus Profile Results in Raffinate Ponds Area Wells Subset of wells routinely sampled, 2000–2017

Site records indicate that wells 0598 and 0884 have likely been sampled consistently at the mid-screen interval. However, hypothetically, if sample depths had varied within these wells (even within the screened interval), there would be significant uncertainty associated with any trend analysis of those data.

4.3.5 Raffinate Ponds Area Summary of Findings

Results of the August–September 2015 chemical profiling indicate that the vertical variation in SC found in former raffinate ponds area wells also applies to sodium, sulfate, and several other major ions. Uranium levels were low in most of the wells profiled in this area of the site. However, in those wells with uranium levels exceeding the 0.044 mg/L standard (0598, 0879, and 0884), uranium concentrations varied widely within the profile. The extent of this variation could not be determined in wells 0598 and 0879 due to obstructions in the wells encountered during sampling. Nonetheless, Phase II results indicate notable variation in uranium chemistry in wells 0598 and 0884, both of which are routinely monitored and screened in the Menefee Formation. Well 0598 is also screened in the Point Lookout Sandstone, which is separated from the overlying Menefee Formation by the Bodo Fault zone. The range in uranium concentrations measured within the screened interval in both of these wells was of sufficient magnitude to impact trend interpretations if sample depths were not consistent.

In general, no strong correlation was found between uranium concentrations and SC in the raffinate ponds area wells. This finding might reflect the very low uranium concentrations measured in most of these wells. On a well-specific basis, an exception was found for well 0598, where a fairly strong linear negative relationship between SC and uranium was found ($r = -0.96$, $r^2 = 0.92$), as well as between uranium and most major ions. However, the strong correlation between SC and uranium in this well was not corroborated by historical monitoring results, which indicated a similar negative, but much weaker, correlation between these two parameters. As found for the mill tailings area wells, the use of SC as a surrogate or indicator of uranium concentrations is not recommended for raffinate ponds area wells. On the basis of the combined data set for wells screened in the Menefee Formation, groundwater salinity (as indicated by SC) is most correlated with sodium and sulfate in this area of the site ($r = 0.86$ and 0.77, respectively).

Full chemical profiles could not be obtained in several wells because of either low water levels or obstructions encountered during sampling. For example, in wells 0607 and 0882, most of the water was in the sump (the phreatic surface was at the screen bottom/sump transition). Full chemical profiles could not be obtained at wells 0598 and 0879 due to obstructions in the well.

Radon-222 profiles were less revealing for former raffinate ponds area wells than for the mill tailings area wells, in part because only three profiles were obtained. However, results for well 0884 (with ^{222}Rn concentration exceeding 700 pCi/L) indicate a "textbook" portrayal of groundwater migration only through the screened portion of the well.

5.0 Shiprock, New Mexico, Disposal Site, Floodplain

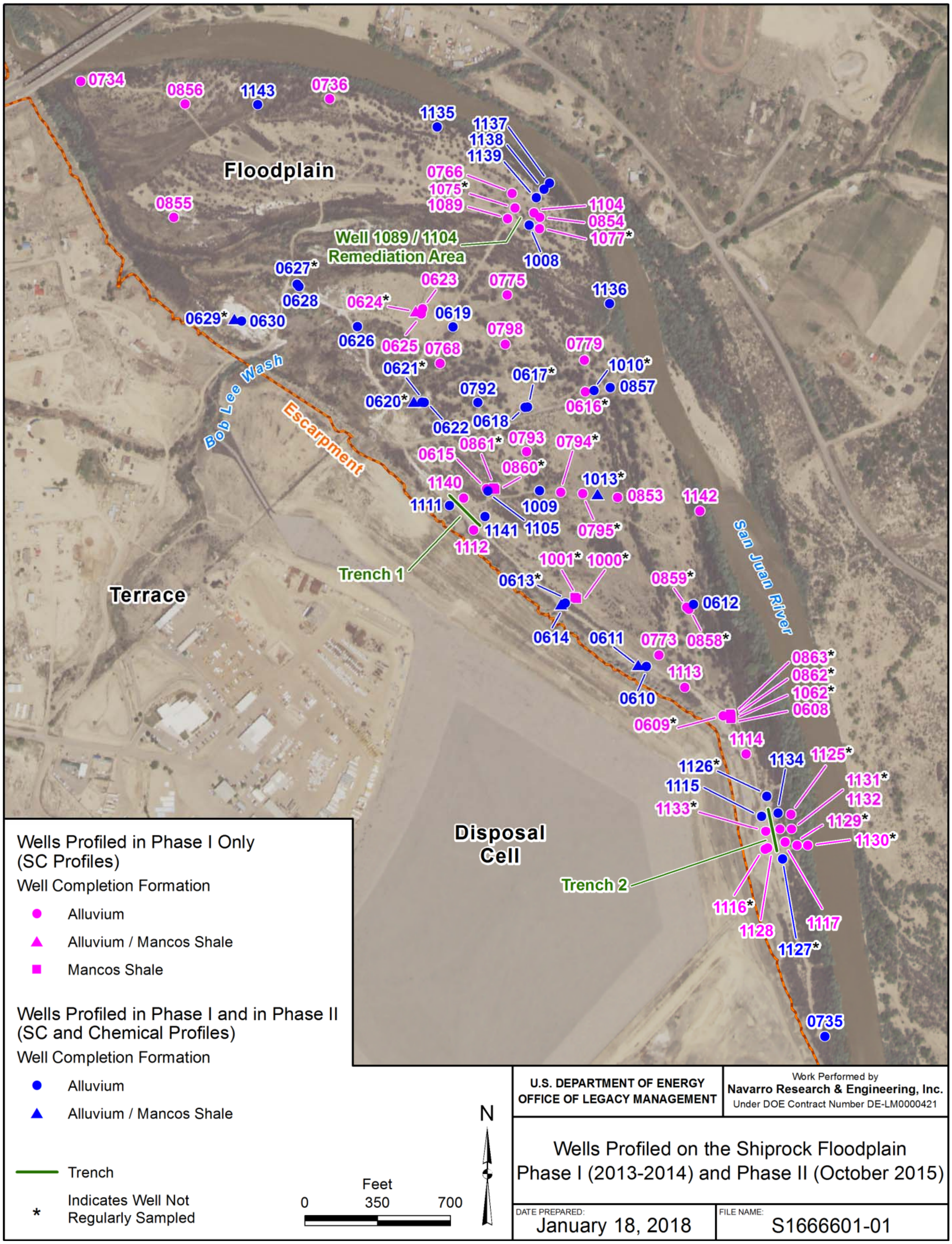
The Shiprock site is located near the town of Shiprock in the northwest corner of New Mexico (Figure 1 and Figure 38). A mill at the site processed uranium and vanadium ores from 1954–1968 on property leased from the Navajo Nation. Remediation of surface contamination, including the stabilization of mill tailings in an engineered disposal cell, was completed in 1986. The former mill was built on a physiographic terrace of Mancos Shale that rises about 60 ft above a floodplain of the San Juan River, which bounds the floodplain to the north and east (Figure 38). For site characterization and groundwater compliance purposes, the site is divided into two distinct areas: the terrace and the floodplain. The disposal cell is located on the terrace portion of the site where only limited profiling took place in Phase I of this study. This evaluation focuses on monitoring wells in the floodplain portion of the site.

As discussed in the introduction, stratification of SC observed in some wells on the Shiprock site floodplain in 2012–2013 was the catalyst for the Variation Project. This stratification was confirmed to be widespread in Phase I of this study, when two rounds of SC profiles were obtained, the first in September 2013 and the second in April 2014 (Figure 38). Based on the prevalence and magnitude of variation in the wells, the floodplain area of the site was chosen for chemical profiling in Phase II (DOE 2015) (Figure 6). SC and chemical profiles were obtained from 36 wells October 19–29, 2015. This well subset was chosen to represent different spatial regions of the floodplain as well as different levels of variability based on the Phase I SC profiles. Although the focus was on highly variable wells (with CVs $\geq$ 0.1; 64%), a proportion of wells with low variation (CV $<$ 0.03; 8%) and mid-level variation (0.03 $\leq$ CV $<$ 0.1; 28%) was also included in this subset. Radon-222 was measured in a subset (10) of the wells (Figure 39). A simplified schematic of well construction information for the 36 wells profiled in Phase II is provided in Figure 40.

5.1 Site Background

Because this report focuses on the Phase II profiling results, only a brief overview of the Shiprock site is provided here. Numerous reports documenting the site's history, characterization, and monitoring efforts can be accessed via LM's website at https://www.lm.doe.gov/shiprock/Sites.aspx. Primary historical site documents include the *Final Site Observational Work Plan for the Shiprock, New Mexico, UMTRA Project Site* (DOE 2000) and the *Final Groundwater Compliance Action Plan for Remediation at the Shiprock, New Mexico, UMTRA Project Site* (DOE 2002a). A more recent evaluation (DOE 2016c) provides a comprehensive evaluation of groundwater flow processes in the floodplain alluvial aquifer. Site data, sample location information, and well construction logs can be found on LM's GEMS website at https://gems.lm.doe.gov/#site=SHP.

During mill operations, uranium, nitrate, sulfate, and other milling-related constituents leached into underlying sediments and contaminated groundwater in the area of the mill site (DOE 2000). Groundwater in gravel, sand, and clay of the floodplain alluvium is contaminated by uranium and other associated constituents from the former mill. The contaminants migrated to the floodplain through fractures in the Mancos Shale. In March 2003, DOE initiated active remediation of groundwater at the site using a pump-and-evaporate system. The floodplain remediation system now consists mainly of two near-river groundwater extraction wells (1089 and 1104) and two collection trenches, Trench 1 and Trench 2 (installed in 2006).



Note: Locations of background wells 0797 and 0850, about 1 mile southeast of well 0735, are not shown.

Figure 38. Shiprock Site Floodplain Wells Profiled for the Variation Project, Phases I and II

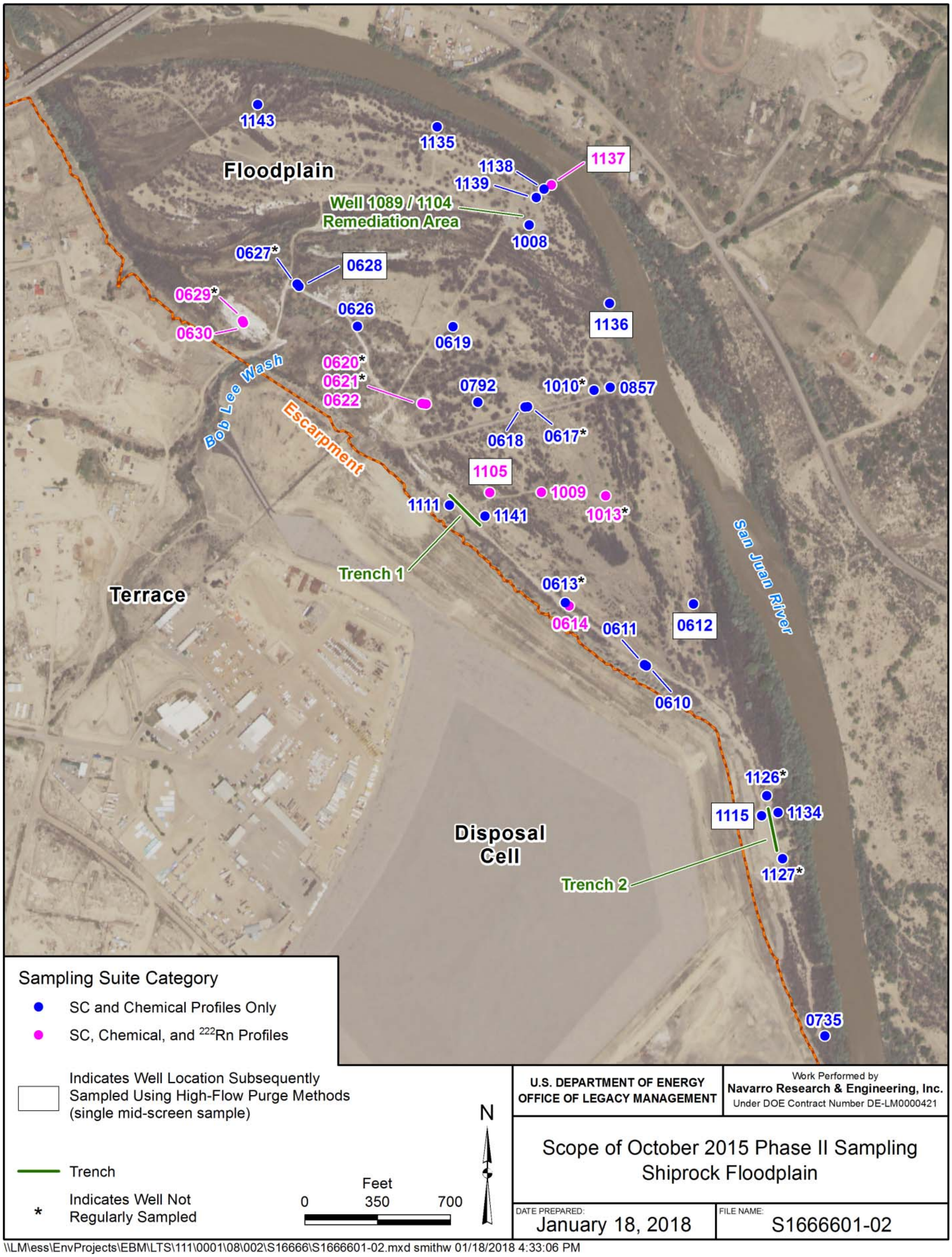
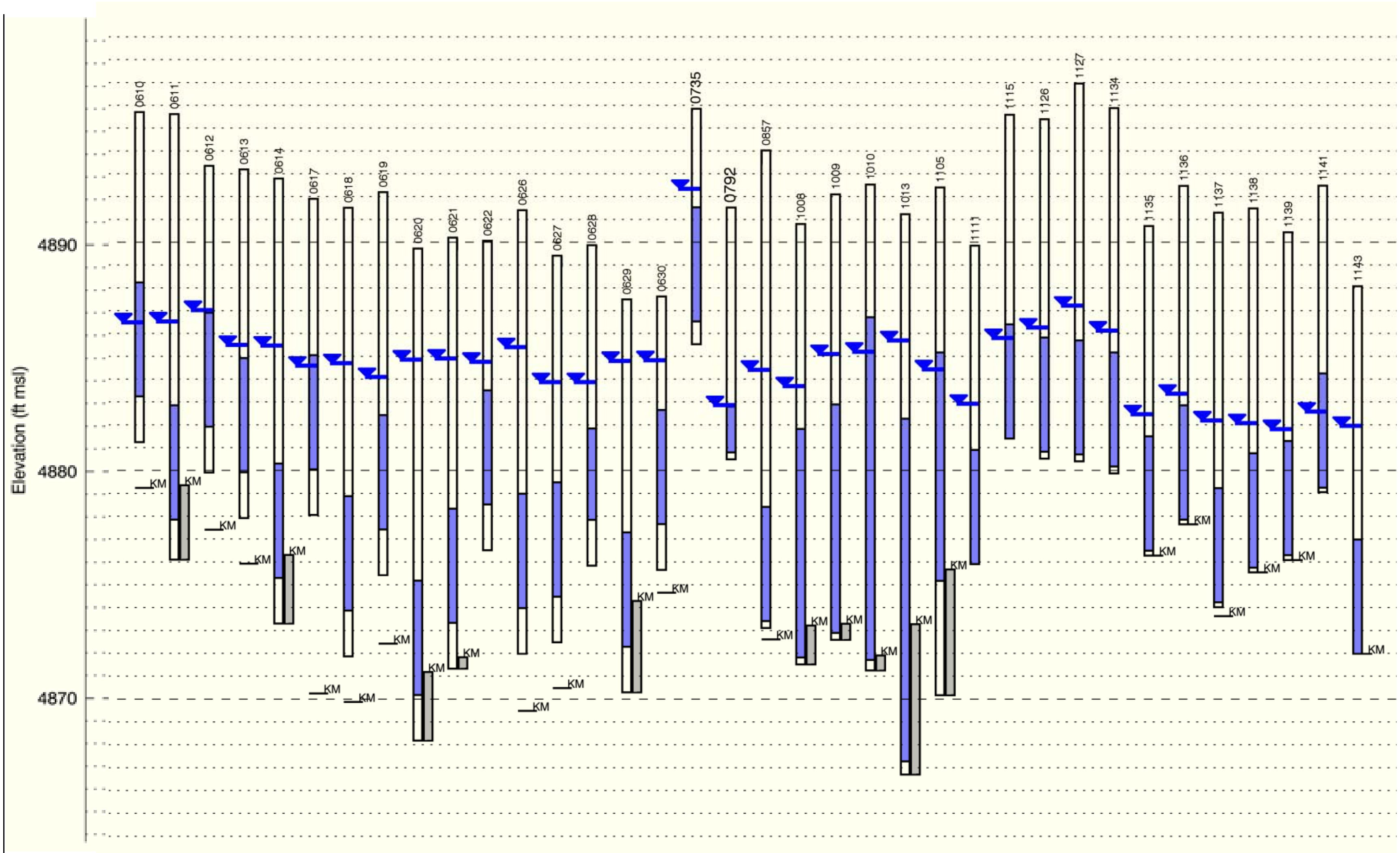


Figure 39. Scope of October 2015 Phase II Profiling, Shiprock Site Floodplain



Inverted blue triangles show the latest measured groundwater elevations (from the March 2017 semiannual sampling event).
Black rectangles show the well casings; well screens are shaded blue. Well screens are 5 ft long except for the following:
well 0628 (4 ft); 0792 (2 ft), wells 1008, 1009, and 1105 (10 ft); and wells 1010 and 1013 (15 ft).
The top of bedrock (the Mancos Shale, KM) is shown to the right of well screen.

Notes:

Wells are plotted in order of well ID and, therefore, do not reflect horizontal location.
Corresponding well construction logs are available on the LM GEMS website (https://gems.lm.doe.gov/#site=SHP).

Figure 40. Well Construction for Shiprock Site Floodplain Wells Profiled in Phase II

5.2 Hydrogeologic Overview

The floodplain alluvial aquifer (floodplain aquifer) occurs in unconsolidated medium- to coarse-grained sand, gravel, and cobbles that were deposited in former channels of the San Juan River overlying the Mancos Shale that underlies the entire site. The aquifer is hydraulically connected to the San Juan River, which is a source of groundwater recharge to the floodplain aquifer in some areas, but also receives groundwater discharge in other areas (DOE 2016c). In addition to San Juan River flows, the floodplain aquifer also receives some inflow from groundwater in the terrace area via seeps. The floodplain alluvium is as much as 20 ft thick and overlies Mancos Shale, which is typically soft and weathered for the first several feet below the alluvium (DOE 2000).

Most of the 36 wells profiled in Phase II are screened solely in the alluvium. In several wells, screens extend a foot or two into the Mancos Shale bedrock. Most wells profiled have 5 ft long screens. Exceptions include well 0792 (with a 2 ft screen) and other wells with 10–15 ft screens, as noted in Figure 40.

5.3 Phase I Overview

During Phase I of this study, SC profiling was conducted twice on the Shiprock site floodplain: in September 2013 and April 2014. A total of 478 profiles (close to 2800 measurements) were obtained. Most alluvial wells were profiled in both phases, whereas (except for shallow well 0608) wells screened in the Mancos Shale were profiled in 2013 only.

September 2013 profiles were measured during a period of active pumping. At that time, flow rates for Trench 1 and Trench 2 pumping wells were about 13 and 7 gallons per minute (gpm), respectively, and rates of extraction at wells 1089 and 1104, near the San Juan River, were about 5.5 and 2.5 gpm, respectively. The April 2014 profiling effort coincided with the final days of a month-long period during which there was no pumping.

Figure 41 plots the CVs derived for both 2013 and 2014 SC profiling efforts. Although somewhat redundant with material presented in the Phase I report (DOE 2015), this figure illustrates the magnitude and prevalence of stratification in SC in floodplain wells. The greatest degree of variation was observed in the Trench 1 and Trench 2 areas, the 1089/1104 remediation area, and other areas coinciding with the highest-concentration portions of the uranium plume (discussed below). The northwest portion of the floodplain, where well installations are more sparse, is characterized by relatively low variation in the SC profiles (with CVs <0.1 and in most cases <0.03). Uranium concentrations are lower in this region relative to the remaining portion of the floodplain (but still elevated relative to standards) (Figure 42a).

To illustrate the distribution of uranium in groundwater, Figure 42 presents a bubble plot of uranium, sulfate, and nitrate concentrations measured in samples collected during the March 2017 semiannual monitoring event. Despite apparent declines in contaminant concentrations discussed in site monitoring reports (e.g., DOE 2018a), Figure 42 illustrates that uranium and sulfate are still elevated relative to groundwater standards in most regions of the floodplain. In contrast, based on the March 2017 semiannual monitoring results, elevated nitrate is generally limited to wells at the base of the escarpment.

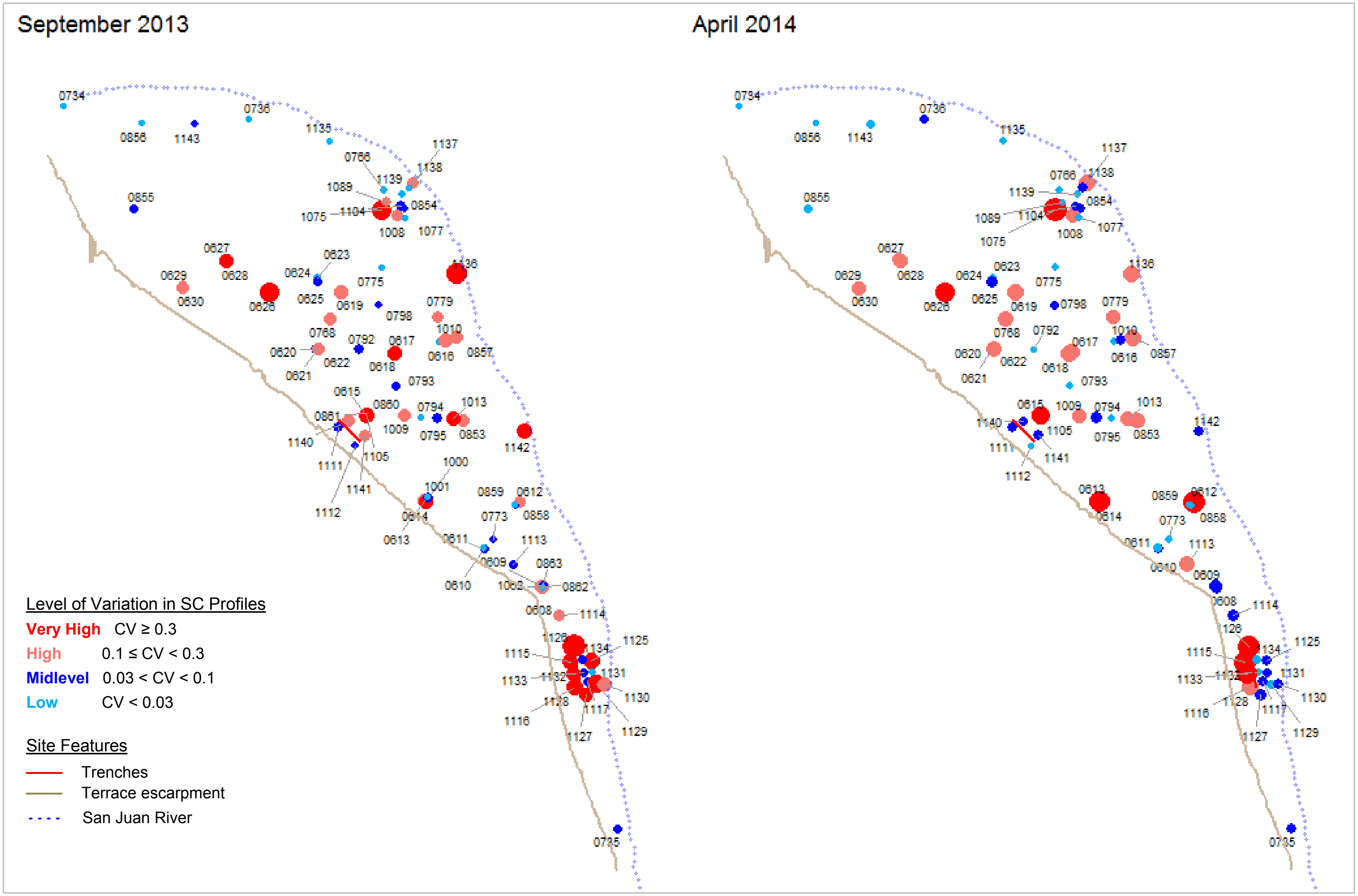
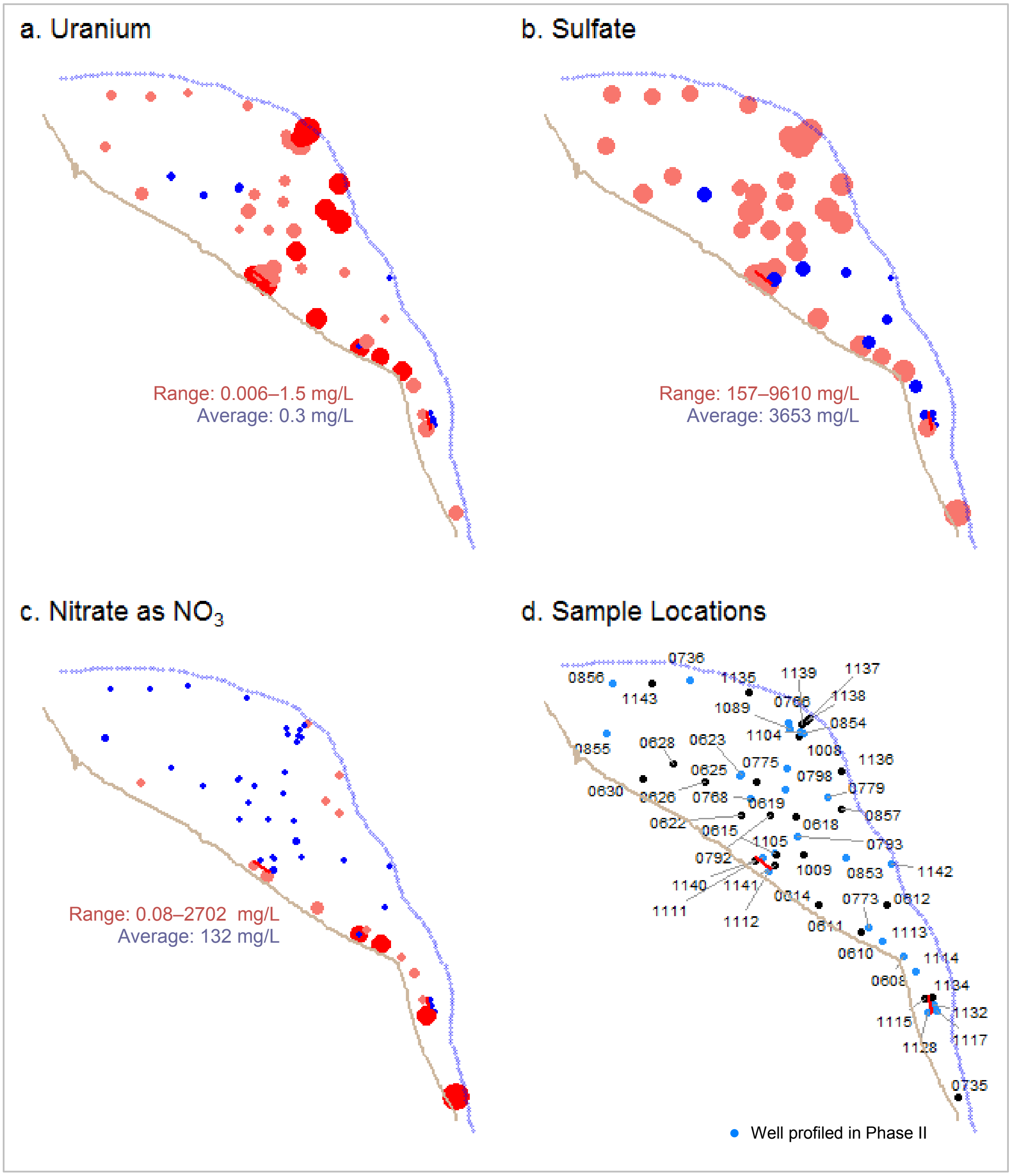


Figure 41. Variation in Phase I SC Profiles Based on the CV, Shiprock Site Floodplain



Diameter of circles proportional to magnitude of result:

- Result < standard
- Standard ≤ result < 10 × standard
- Result > 10 × site standard
- Trenches (Trench 1 and 2)

Note:
Corresponding standards are 0.044 mg/L uranium, 2000 mg/L sulfate (background), and 44 mg/L nitrate as NO_3.

Figure 42. Bubble Plot of Uranium, Sulfate, and Nitrate Concentrations in Shiprock Site Floodplain Wells March 2017 Semiannual Monitoring Event

Figure 43 is a map of the average CVs from Phase I showing only the 36 wells selected for profiling in Phase II. Although most wells selected for chemical profiling in Phase II of this study had highly varying SC profiles, some wells with low- to midrange variability were also profiled. This was done to test the hypothesis that little to no variation in SC would correlate with similar lack of variation in site contaminants.

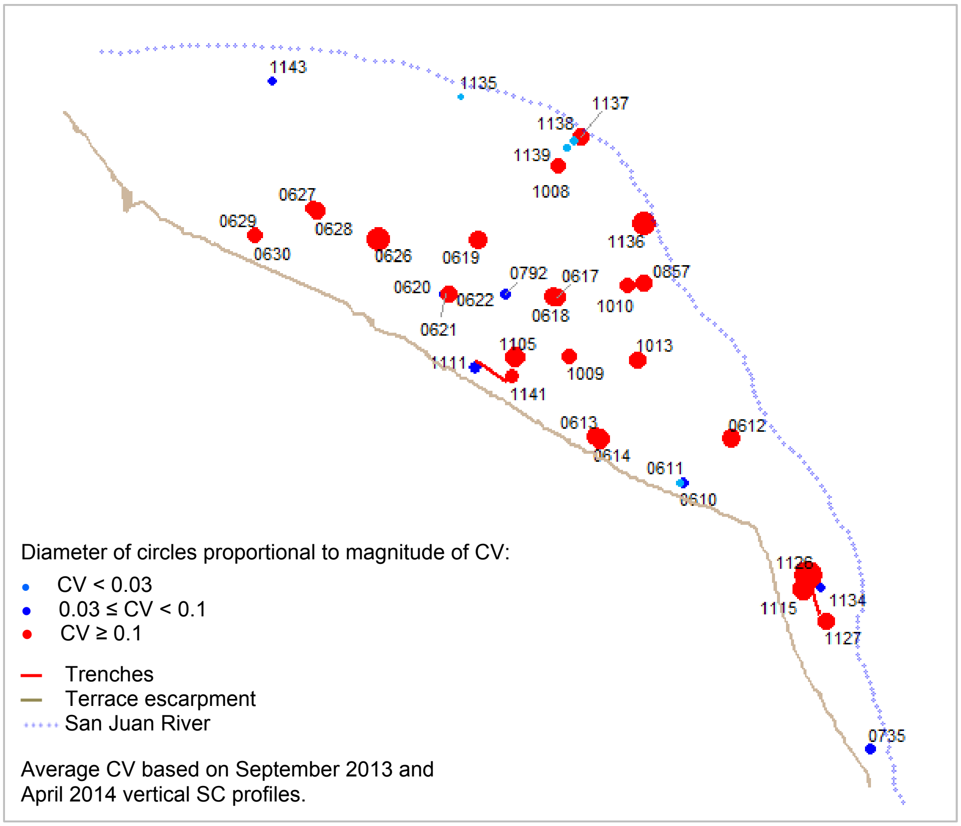


Figure 43. Map of Phase I CV for Subset of Wells Profiled in Phase II

5.4 Phase II Specific Conductance and Analyte Profile Results

Phase II of this study yielded 550 variable profiles for the Shiprock site floodplain wells (36 wells × 15 parameters + 10 ^{222}Rn profiles). Due to the volume of data, this section focuses primarily on results for SC and the primary site contaminants—uranium, sulfate, and (to a lesser extent) nitrate. Radon-222 profiles are also discussed, as these results further understanding of groundwater conditions in the subset of wells profiled for this parameter. Detailed vertical profile results are provided in Appendix E, which includes all associated data: plotted first by analyte (Appendix E-1) and then by well (Appendix E-2).

Because of the large number of wells profiled on the Shiprock site floodplain (relative to the Durango site), four categories of profiles were derived to focus the discussion and better summarize results. Although based largely on the SC profiles, these categories were also defined based on the combination of patterns observed not only for SC but also for uranium, sulfate, and other parameters (as shown in the detailed well-specific plots provided in Appendix E-2).

These categories are described as follows:

- Group 1—*Within-Screen Variation*. Increasing SC with depth within the screened interval, often correlating with concomitant increases in uranium, sulfate, and other parameters.
- Group 2—*Screen Effect*. Marked increase in SC at the upper casing/screen transition followed by fairly constant SC with depth within the screened interval.
- Group 3—*Dead-Zone Variation*. Abrupt shift in profile corresponding to the sump or Mancos Shale region of the well.
- Group 4—*No Consistent Pattern in Profiles*. Erratic contaminant profiles and no consistent pattern across analytes within a well.

Table 6 summarizes these groups and identifies the wells comprising them. It is important to note that these are very general categories (the approach here was to lump items together rather than split them), and there are exceptions. For example, several of the wells categorized as having predominantly dead-zone variation (Group 3) also exhibited within-screen variation; in these cases, the dead-zone variation was more prominent. Although some wells selected as comprising Group 4 had SC profiles more characteristic of another category (e.g., Group 1 or 3), signatures for other parameters were erratic and did not correlate with the SC profile. Four of these wells—0621, 0626, 1135, and 1143—are in a western floodplain area characterized by relatively low uranium concentrations. Again, although somewhat arbitrary, the main purpose of this categorization was to focus this evaluation and to select representative wells for discussion.

Table 6. Profile Categories Derived for Shiprock Site Floodplain Wells, Phase II

Group No.	Profile Category	Description	Wells
Group 1	Within-screen variation	Measurements of SC and other parameters are fairly constant in the blank casing above the screened portion of the well (in those wells with a higher phreatic surface) but then increase (at times markedly) over the screened interval.	0610, 0613, 0617, 0618, 0629, 0630, 0792, 0857, 1010, 1115, 1127, 1134, 1136, 1137, 1141
Group 2	Screen effect	Marked increase in measurements in region of the upper casing/screen transition, but SC consistent within the screened interval. Only three wells fell into this category.	1126, and near-river wells 1138 and 1139
Group 3	Dead-zone variation	SC and other parameters are constant through the screened interval but then increase steeply in the lower (unscreened) blank casing. In some wells, this region coincides with the bedrock contact.	0612, 0614, 0620, 0622, 0627, 0628, 1008, 1009
Group 4	No consistent pattern in profiles (random variation)	SC and other profiles characterized by noise or random variation, in some cases erratic. Also includes those wells with no apparent agreement or correlation between SC, uranium, and other parameters.	0611, 0619, 0621, 0626, 0735, 1013, 1105, 1111, 1135, 1143

For each well profiled in Phase II, Table 7 summarizes key information, including corresponding profile categories, zone(s) of completion, and number of samples collected. For some wells, key observations regarding analyte profiles (e.g., for ^{222}Rn) or downhole video camera survey results (summarized in Appendix B) are also provided.

Table 7. Summary of Wells Profiled at the Shiprock Site, Phase II Study

Well	Phase I SC CV[a]	Phase II Sample *n*[b]	Profile Category[c]	Description
0610	0.06	4	Group 1	Well at base of escarpment colocated with well 0611
0611 (AL-KM)	0.02	7	Group 4	Well at base of escarpment colocated with well 0610
0612	0.30	6[d]	Group 3	Hyporheic well
0613*	0.25	6	Group 1	Base of escarpment
0614 (AL-KM)	0.36	11[e]	Group 3	Base of escarpment
0617*	0.22	6	Group 1	Central floodplain
0618	0.28	12	Group 1	Central floodplain
0619	0.26	9	Group 4	Central floodplain
0620* (AL-KM)	0.05	17[e]	Group 3	Central floodplain
0621*	0.03	13[e]	Group 4	Central floodplain
0622	0.23	9	Group 3	Central floodplain
0626	0.53	11	Group 4	Western floodplain
0627*	0.14	12	Group 3	Western floodplain
0628	0.24	8[d]	Group 3	Western floodplain
0629* (AL-KM)	0.07	16[e]	Group 1	Western floodplain
0630	0.18	11[e]	Group 1	Western floodplain
0735	0.05	4	Group 4	Southernmost well profiled on floodplain
0792	0.04	3	Group 1	Central floodplain
0857	0.21	11	Group 1	Central floodplain
1008 (AL-KM)	0.16	11	Group 3	Well 1089 area
1009	0.19	11[e]	Group 3	Hyporheic well
1010*	0.18	13	Group 1	Central floodplain
1013* (AL-KM)	0.23	18[e]	Group 4	Hyporheic (river loss) area well
1105	0.33	15[d,e]	Group 4	Trench 1
1111	0.08	4	Group 4	Trench 1
1115	0.41	6[d]	Group 1	Trench 2 west
1126*	0.80	7	Group 2	Trench 2 west
1127*	0.20	8	Group 1	Trench 2 east
1134	0.04	8	Group 1	Trench 2 east
1135	0.02	6	Group 4	Western floodplain
1136	0.54	5[d]	Group 1	Central floodplain
1137	0.20	9[d, e]	Group 1	Well 1089 area
1138	0.03	6	Group 2	Well 1089 area
1139	0.02	7	Group 2	Well 1089 area
1141	0.11	5	Group 1	Trench 1
1143	0.03	10	Group 4	Western floodplain well

Notes:
***Well *not* routinely sampled (i.e., not sampled during semiannual March and September monitoring).
AL-KM denotes well screened in AL and KM. All other wells listed are screened solely in the alluvium.
[a] CVs listed are averages of September 2013 and April 2014 Phase I SC profiles (DOE 2015), with CV categories defined as:
0.30 **High** (CV ≥ 0.1), 0.06 **Mid-level (**0.03 ≤ CV < 0.1), 0.02 **Low** (CV < 0.03).
[b] Number of samples (*n*) collected for chemical analysis.
[c] Group 1 = within-screen variation, Group 2 = screen effect (results homogenous within the screened interval), Group 3 = dead-zone variation, and Group 4 = no consistent pattern in profiles.
[d] Samples also collected at mid-screen interval using 3-bore volume purge methods.
[e] Well also profiled for ^{222}Rn

A summary of field observations and downhole video profile results is provided in Appendix B.3.

Specific Conductance Profiles

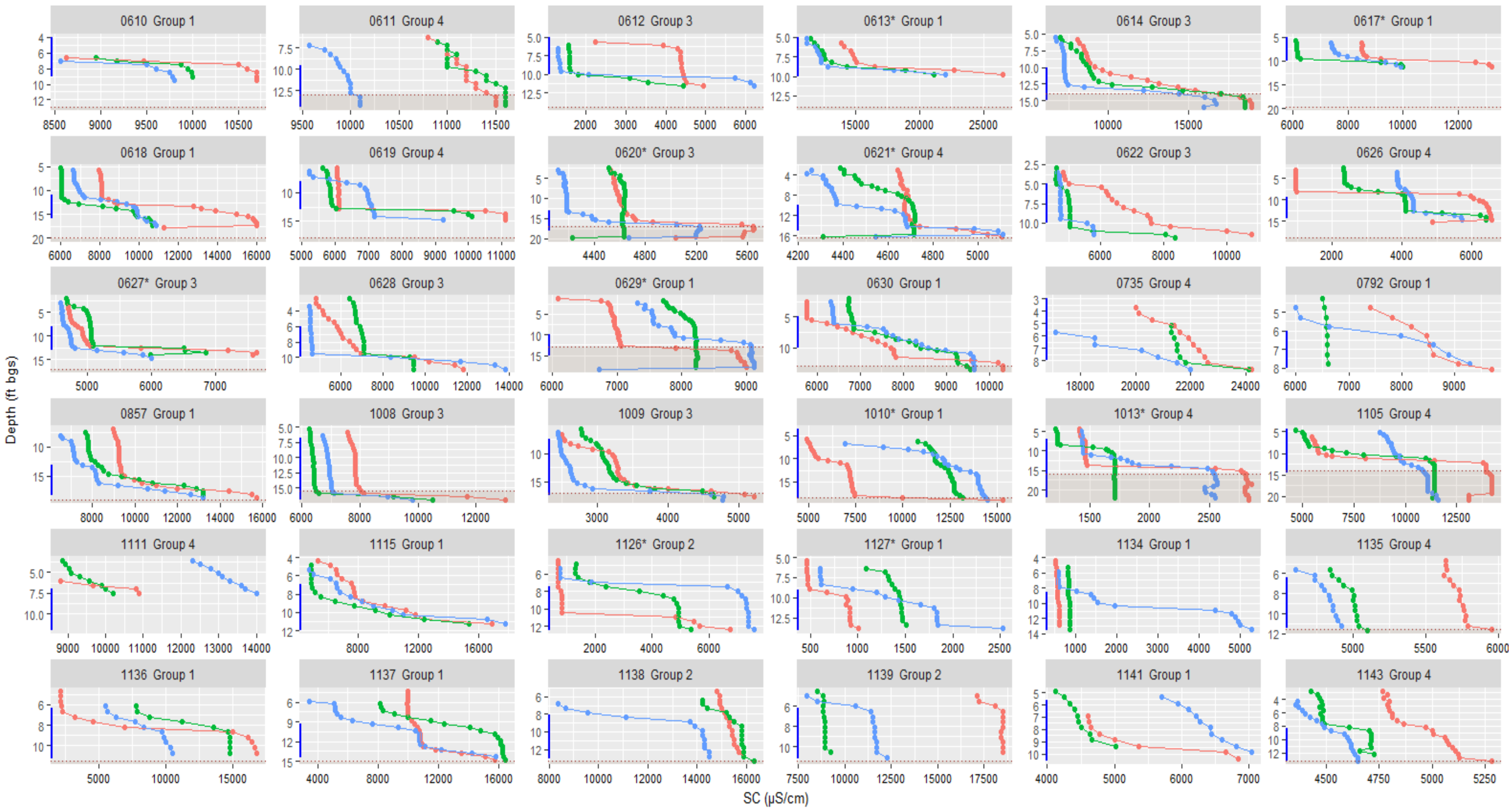
Figure 44 plots SC by depth for all 36 Shiprock site floodplain wells profiled in October 2015. Phase I (September 2013 and April 2014) results are also shown. In this figure, the strip text (subplot identifier) lists each well followed by the corresponding profile category. Wells that are not routinely sampled are also identified. As shown in Table 7, the majority of wells profiled in Phase II are routinely sampled (in March and September of each year).

In general, SC profiles obtained during the three events are similar (in shape and SC magnitude). However, there are exceptions, more so with regard to SC magnitude than the shape or trend in the profile. The most obvious temporal difference is apparent for well 1134 (east of Trench 2), which had very little variation in both Phase I SC profiles (CV = 0.04) and low SC relative to most wells on the floodplain (<1000 µS/cm). This was not the case in Phase II, when SC varied widely, increasing by nearly 4000 µS/cm (from 1461 to 5288 µS/cm) within the screened interval. Other wells with notable differences in the SC profiles (in terms of both shape and magnitude) include wells 0792, 1010, 1013, and 1126.

The factors accounting for the differences noted above are not known at this time. Possible explanations include seasonal changes or localized influences of remediation pumping, or both. For example, the Phase I (September 2013 and April 2014) and Phase II (October 2015) SC profiles were obtained at different times of the year under different groundwater and San Juan River flow conditions, as well as different pumping conditions. The remediation system was operating during the first September 2013 profile, whereas the April 2014 and September 2015 profiles were obtained when the pumps were shut down.

Apart from the exceptions noted above, Phase I and II profiles are overall very similar. The predominant pattern is that SC increases with depth in all wells profiled, at times notably so. This is more readily apparent in Figure 45, which plots SC by depth based only on the Phase II profile results. Because each well has unique *x*- and *y*-axis scales, points are color-coded based on the corresponding CV to facilitate identification of wells with high or, conversely, low variation. Using the first four wells as examples (0610, 0611, 0612, and 0613), the increase in SC with depth is common to all wells and the profile shapes are somewhat similar. In the first case (well 0610), the increase in SC encompasses a fairly small range (about 1000 µS/cm) over a shallow (8–10 ft) interval (moderate variation). In the second case (well 0611), there is a somewhat stepwise pattern but over an even smaller range (approximately 500 µS/cm) in SC (low variation). In the third case (well 0612), SC more than quadruples within the span of the 5 ft screen and 1 ft sump region, from 1316 to 6202 µS/cm (very high variation). In the final case (well 0613), SC nearly doubles (from 11,200 to 22,000 µS/cm) within the screened interval (high variation).

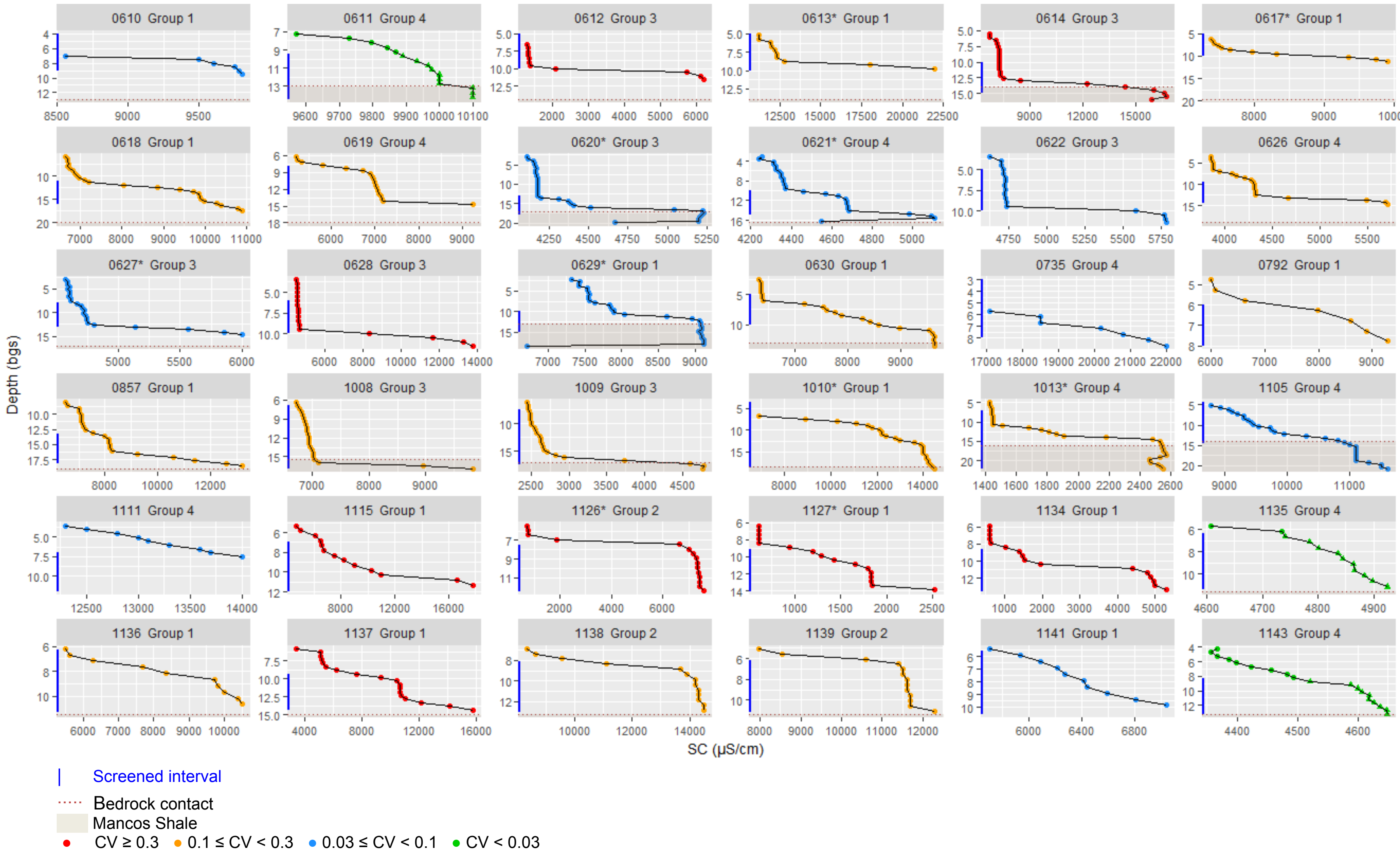
Figure 46 plots the same data as shown in Figure 45, but the *x*- and *y*-axis scales are common. Points are color-coded to indicate the portion of the well where the measurement was taken (● casing, ● screen, or ● sump). The mean SC derived is shown (with a vertical dotted line) to facilitate identification of high versus low salinity wells relative to the Shiprock site floodplain data set. Because of the wide range in SC—598 µS/cm in well 1134 to 22,000 µS/cm in well 0613—the *x*-axis scale in this figure is logarithmic. Using this semilog scale plotting approach, any deviations in the points (from a vertical line) are indicative of fairly significant variation in the SC profiles. Some notable examples include wells 0612, 1134, 0628, and 1115.



- Phase I, September 2013 (pumping)
- Phase I, April 2014 (non-pumping)
- Phase II, October 2015 (non-pumping)
- | Screened interval
- ..... Bedrock (Mancos Shale) contact

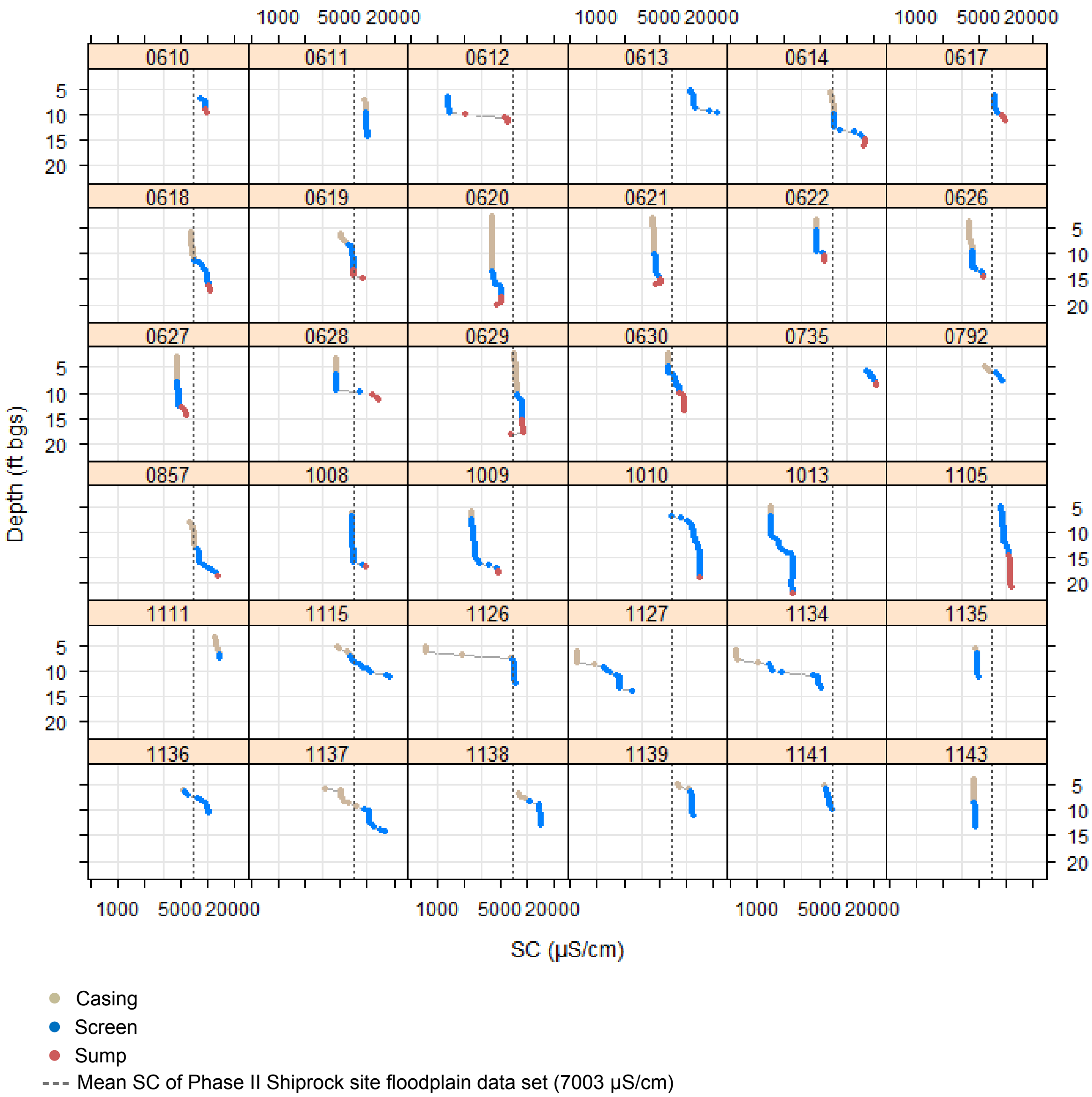
Notes:
*Well is not routinely sampled. Well IDs are followed by the following profile categories defined in Table 6:
Group 1 = Within-screen variation; Group 2 = Screen effect (results homogenous within the screened interval); Group 3 = Dead-zone variation; Group 4 = No consistent pattern in profiles
All SC measurements taken at 0.5 ft intervals; the top measurement is roughly equivalent to the phreatic surface (the first SC measurement taken at the next 0.5 ft interval below the top of the water table).

Figure 44. SC Profiles in Shiprock Site Floodplain Wells: Phase I Versus Phase II Results



Notes:
*Well is not routinely sampled. Well IDs are followed by the following profile categories defined in Table 6:
Group 1 = Within-screen variation; Group 2 = Screen effect (results homogenous within the screened interval); Group 3 = Dead-zone variation; Group 4 = No consistent pattern in profiles

Figure 45. Phase II SC Profiles in Shiprock Site Floodplain Wells, Color-Coded by CV



Note:
A logarithmic *x*-axis scale may mask the magnitude of change in SC with depth. Using this plotting approach, even small changes in the *appearance* of the slope of the plotted points can correspond to a large range in SC. Using well 0619 as an example, despite the apparent small shift in the corresponding plot above, SC spanned a range of about 4000 µS/cm, from 5216 to 9230 µS/cm.

Figure 46. Phase II SC Profiles in Shiprock Site Floodplain Wells, Common Scales

Although the prevalence of highly varying SC profiles (e.g., with CV > 0.1) was already demonstrated in the Phase I report (DOE 2015), these conclusions have been reiterated here because they form the basis for subsequent discussions of vertical trends observed for other parameters (e.g., uranium), as well as the assessment of correlations addressed in Section 5.5.

Uranium, Sulfate, and Other Analyte Profiles

Before focusing on the Phase II profile results for the key parameters (uranium and sulfate), this section begins with a brief discussion of generalized trends for all analytes. A corresponding summary is provided in Table 8. As discussed in greater detail in the text following this summary, uranium concentrations varied in all well profiles, often in a manner appearing consistent with the SC profiles. Similar variation in the vertical profiles was found for sulfate.

Along with sulfate, concentrations of most remaining major ions—in particular sodium, alkalinity, and magnesium—also vary significantly in some wells. In a number of cases, this variation appears to correlate with that in the corresponding SC profiles. Variable-specific profile results demonstrating this conclusion are provided in Appendix E-1, and pairwise correlations are examined later in this section.

Consistent with the corresponding plume map shown in Figure 42, nitrate was detected at elevated levels (i.e., exceeding the 44 mg/L standard) in only about one-third of the 36 wells profiled. Within that subset, however, nitrate levels also varied with depth, at times markedly. Unlike observations for Durango site wells, organic carbon (DOC and TOC) profiles indicate a consistent pattern of increasing with depth in most Shiprock site floodplain wells, often sharply increasing in the bottom portion of the well coinciding with the sump or (in a few wells) the Mancos Shale region.

Of the 325 samples analyzed for this site, dissolved iron was below the detection limit (0.05–0.2 mg/L) in all but three of the samples. The few detections were sump measurements (at the well bottom) in wells 1008 and 1139 (0.15–0.16 mg/L) and a mid-screen measurement in well 1127 (0.06 mg/L). Total iron was detected in about 50% (166 of 325) of the samples. Apart from elevated levels of total iron in sump portions of a few wells, no noteworthy trend with depth is apparent in most of the wells (Appendix E-1). Although pH varies within the neutral range of 7.4 to 8.6, there is no apparent pattern to this variation in any of the wells.

The remaining discussion focuses on uranium—the primary indicator of milling-related contamination at this site and the constituent of most interest. Profile results are also discussed for sulfate and nitrate, as these constituents (along with uranium) are used to assess remediation progress at the Shiprock site (DOE 2018a). To evaluate corresponding flow dynamics, ^{222}Rn signatures are discussed for the 10 wells in which profiles were determined.

Table 8. Summary of Observations by Analyte, Shiprock Site Floodplain Wells

Parameter	General Trends
SC	Consistent with Phase I results, SC varied with depth in nearly all wells profiled. Even in those wells where the range in SC was fairly small, for example, western floodplain wells 1135 and 1143 (with a range of only 300 µS/cm), there is still an apparent density gradient. The greatest variation in SC profiles changes was found in wells 0612, 1134, 0628, 1126, 1115, 1127, 0614, and 1137. The highest SC was measured in wells 0613 and 0735.
Uranium	Uranium concentrations varied in all well profiles, often in a manner appearing consistent with the SC profiles. Wide variation in uranium profiles as well, in many cases correlated with SC and major ion signatures. Uranium concentrations were highest in base of escarpment well 0613 (1.4–4.6 mg/L).
Sulfate	In most wells, vertical profiles for sulfate were similar in shape to those obtained for SC. Of all the major ions, this parameter is most strongly associated with SC, as evidenced by r = 0.96 for the data from the screened interval data set for all 36 wells combined (Figure 59). In several wells, sulfate concentrations doubled or even tripled within the screened interval.
^{222}Rn	About half of the 10 wells profiled had low ^{222}Rn concentrations suggesting stagnant conditions (^{222}Rn < 50 pCi/L). Radon-222 in some wells (e.g., well 1009) indicated groundwater flow through the screen, while in others, low levels indicated stagnant conditions.
Remaining major ions	Along with sulfate, concentrations of most major ions—in particular sodium, alkalinity, and magnesium—vary significantly in some wells. Although there are exceptions, in general, the major ion signatures correlate with the SC profiles.
Nitrate as NO_3	Nitrate was detected at elevated levels (i.e., >44 mg/L) in only about one-third of the 36 wells profiled. Within that subset, nitrate levels also varied with depth in a manner generally consistent with SC, at times markedly. Consistent with routine monitoring data, nitrate levels are highest in wells located at the base of the escarpment and the Trench 2 area.
DOC and TOC	DOC and TOC profiles are very similar (r = 1 for screened interval data); both indicate a consistent pattern of increasing with depth in most Shiprock site floodplain wells. In several wells, DOC and TOC concentrations sharply increase in the bottom portion of the well coinciding with the sump or (in a few wells) the Mancos Shale region.
Iron, total and dissolved	Dissolved iron was detected in only 3 of the 325 samples, suggesting oxidized conditions in most wells (given total iron content). Apart from elevated levels in sump portions of a few wells (e.g., well 1013), no noteworthy trend in total iron concentrations with depth is apparent in most of the wells profiled.
pH	The pH levels varied within the neutral range (7.4–8.6); no apparent signature or trend in most well profiles.

Note:
Detailed plots of profile results are provided in Appendix E-1 for each of the 16 individual analytes.

Figure 47 plots uranium concentrations by depth in all 36 Shiprock site floodplain wells profiled in Phase II. Figure 48 plots the same data, but with scales that are common for both the *x*- and *y*-axis variables. As shown in these figures, uranium concentrations increase with depth in most of the wells profiled. In some cases—for example, wells 0611, 0629, and 1008—these increases correspond to the sump or bedrock contact. In near-river wells 1136 and 1137, there is a notable stepwise progressive increase through the screened interval. Other wells (e.g., well 0614) are characterized by *both* within-screen variation and increasing uranium concentrations in the sump or Mancos Shale region. Some of the most variable uranium profiles (based on all well portions shown in Figure 48) were measured in wells 0612, 0627, 0628, and 1134.

A reasonable data evaluation approach might be to exclude or discount upper casing or even sump profile measurements (as was done for deeper Durango site wells). However, for the Shiprock site floodplain data set, these measurements are not ignored for two reasons. First, it is known that, in the past, historical routine monitoring samples were likely collected from the sump region in several floodplain wells. In these cases, the full profile results might inform interpretations of historical trends. Second, downhole video profiles taken in April 2016 (Appendix B) indicated discrepancies in screen placement in a number of wells profiled. These two factors, combined with, at times, highly varying water levels in these relatively shallow alluvial wells, warrant examination of the entire profiles rather than the screened intervals only.

Wells installed in the Shiprock site floodplain differ from many of the Durango site wells (especially those in the raffinate ponds area) in that uranium concentrations exceed the 0.044 mg/L MCL in most wells (Figure 42 and Figure 47). Nonetheless, the variation found in most uranium profiles is of a sufficient magnitude to influence interpretations of historical trends if sample depths are not considered in the monitoring program. As shown in Figure 49, in a few wells (e.g., 0612, 0628, and 1134), the range in uranium concentrations measured vertically includes values both above and below the 0.044 mg/L standard.

Although in most cases uranium concentrations increase in a manner generally consistent with the SC profiles (this is addressed in detail in Section 5.5), some of the uranium profiles are erratic. For example, uranium concentrations in well 1013 are highest in the upper casing and screened portion of the well, decreasing markedly in the mid-screen region, and then increasing again. This profile shape is distinctly different from the classic mid-screen increase found for SC (Figure 45).

Figures 49 and 50 plot corresponding results for sulfate, a constituent used to assess remediation progress at the site and also a major ion (the vertical profile could help explain the stratification in SC). In previous figures (e.g., Figure 48), results exceeding a corresponding standard or background level are plotted in red to distinguish high versus low constituent concentrations. Because the 2000 mg/L site background level is exceeded in most samples, a different color scheme is used (results <2000 mg/L are shown in blue). Similar to corresponding SC profiles, sulfate concentrations increase with depth in most wells, in many cases within the screened interval. Sulfate concentrations in well 1137, in the well 1089/1104 pumping region and near the San Juan River, nearly double within the screened interval (from 5450 to 10,200 mg/L). The most marked shifts are apparent in Figure 50, in which data are plotted on a semilog scale. As shown in this figure, sulfate concentrations span a wide range vertically in wells 0612, 1127, 1134, and 1137.

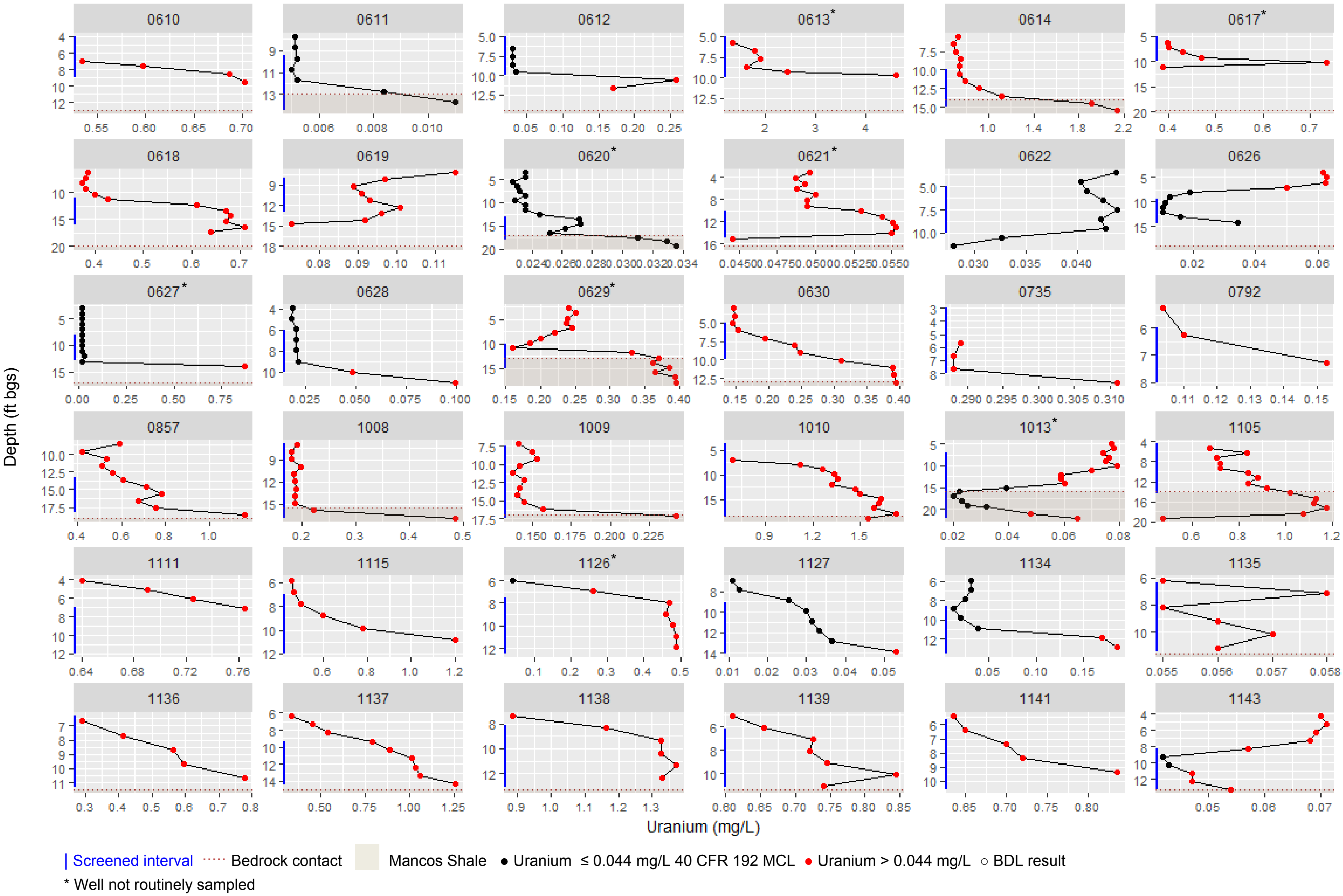
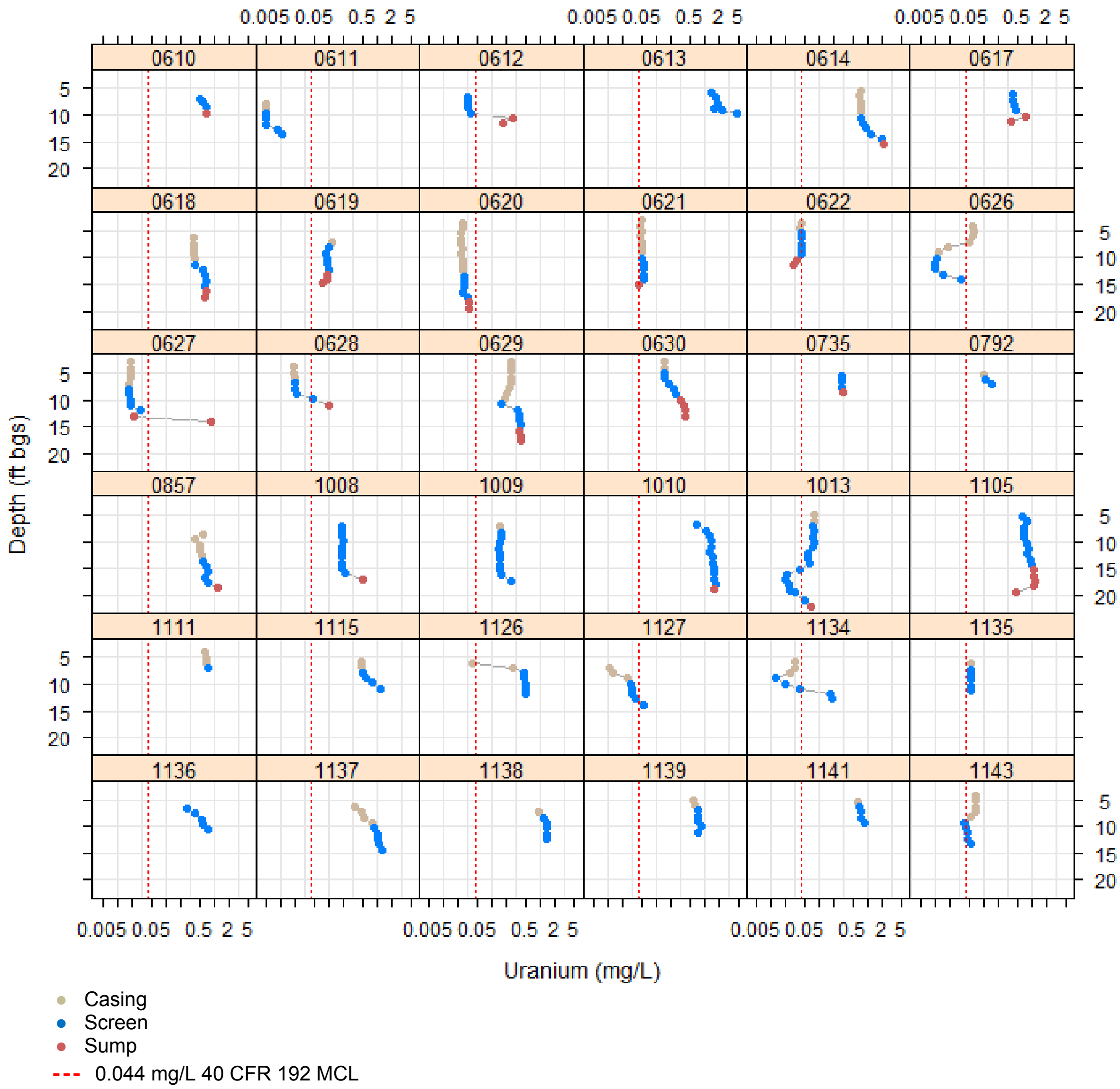


Figure 47. Uranium Profiles in Shiprock Site Floodplain Wells, October 2015: Unique Scales



Note: Use of a logarithmic *x*-axis scale may mask the magnitude of change in uranium concentrations with depth.

Figure 48. Uranium Profiles in Shiprock Site Floodplain Well Profiles, October 2015: Common Scales

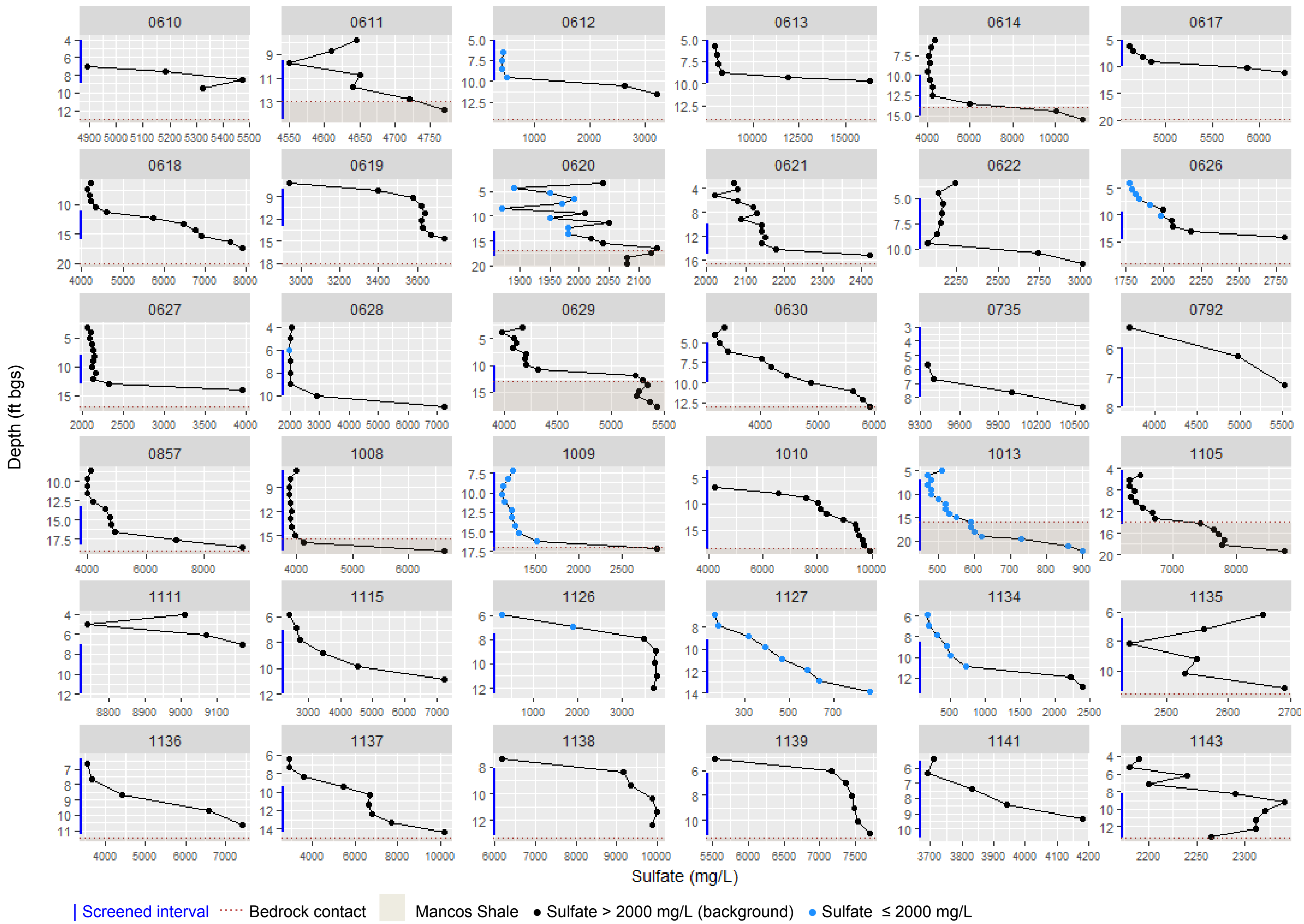
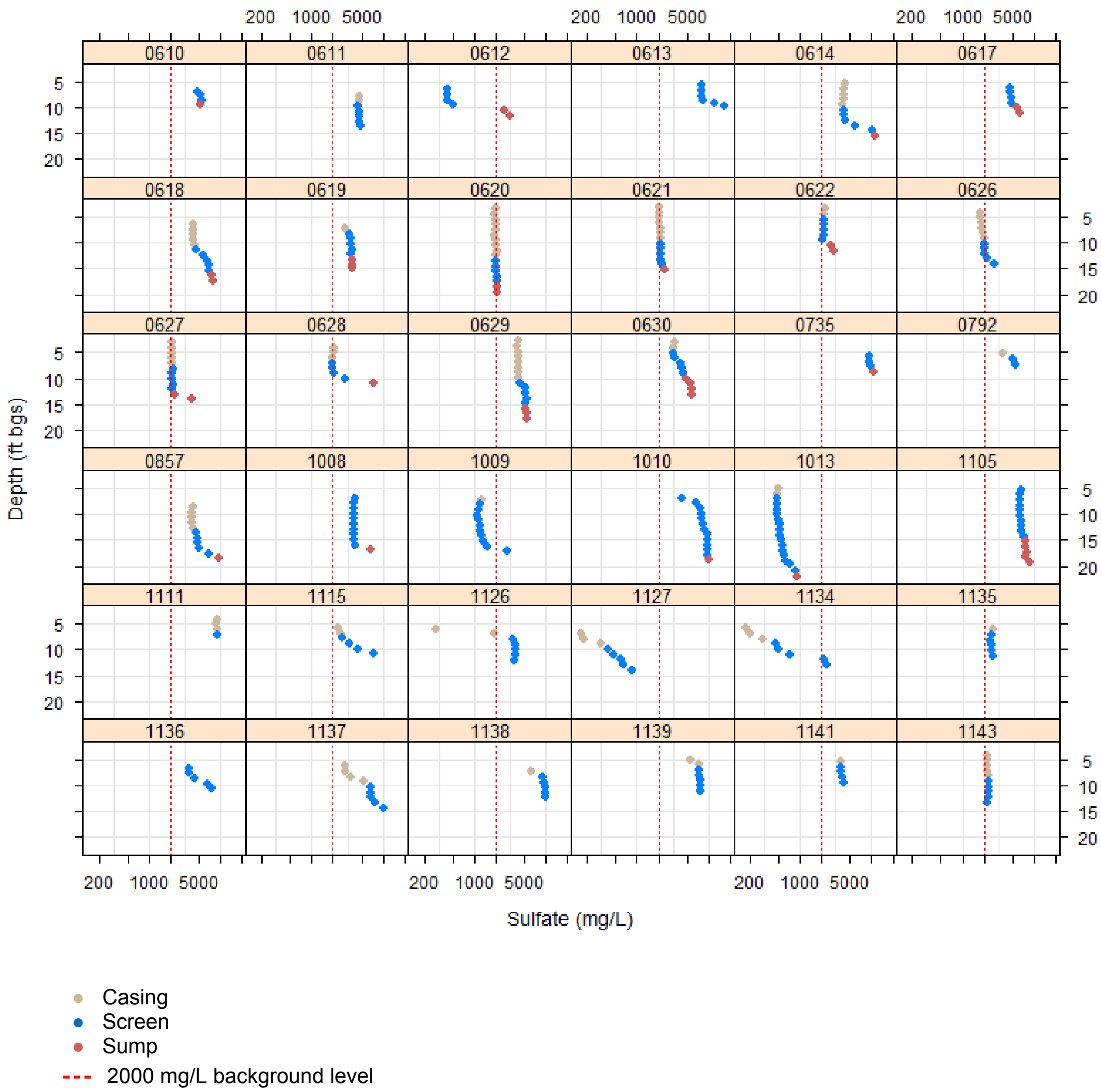


Figure 49. Sulfate Profiles in Shiprock Site Floodplain Wells, October 2015: Unique Scales



Note: A logarithmic *x*-axis scale may mask the magnitude of change in sulfate concentrations with depth.

Figure 50. Sulfate Profiles in Shiprock Site Floodplain Wells, Common Scales

Vertical profile results for nitrate are shown in Figure 51 (unique scales) and Figure 52 (common scales). Although nitrate is used to assess remediation progress (e.g., DOE 2018a), the corresponding plume is smaller than the uranium and sulfate plumes (Figure 42). This is partly reflected in the profile results, as the greatest variation is generally limited to wells with nitrate (as NO_3) exceeding the corresponding 44 mg/L 40 CFR 192 standard. Wells with notable variation in the nitrate profiles include wells 0629 and 0630, at the base of Bob Lee Wash (Figure 39).

In well 0630, nitrate concentrations more than triple within the screened interval, from about 50 to over 150 mg/L. Since 2010, this well has been characterized by wide fluctuations (increases) not only in nitrate but in sulfate and uranium. Corresponding detailed profile results are examined later in this section. Nitrate also increased markedly in wells 0614, 1010, 1126, 1127, and 1134. In contrast, albeit at low concentrations, nitrate concentrations decreased within the screened interval in other wells (0618, 1008, 1009, and 1013). Some authors (e.g., Long et al. 2000) suggest that various biodegradation processes may influence the concentrations of nitrate and potentially other contaminants in the floodplain alluvial aquifer. The extent to which these biogeochemical processes might explain the observed decreases in nitrate concentrations in these wells is not known.

To demonstrate the variation in the vertical profiles measured for all parameters (in addition to those for the key analytes illustrated in Figures 44 through 52), the remainder of this section discusses the Phase II results for select Shiprock site wells representative of the profile categories defined previously:

- Group 1—*Within-Screen Variation*: well 0618 (Figure 53) and well 0630 (Figure 54)
- Group 2—*Screen Effect*: wells 1138 and 1139 (Figure 55)
- Group 3—*Dead-Zone Variation*: well 1009 (Figure 56)
- Group 4—*No Consistent Pattern in Profiles*: well 0626 (Figure 57)

Figure 53 plots vertical profiles for all analytes for well 0618, located in the central portion of the floodplain and the uranium plume. A catalyst for this study, this well is a classic example of SC and contaminant stratification within the screened interval. SC varies by about 4000 µS/cm and sulfate concentrations replicate this increasing trend with depth. Uranium concentrations increase in a manner consistent with SC, ranging from 0.4 to 0.7 mg/L within the profile. Despite the obvious variation, this range is small relative to that measured during profiling work that preceded this study (Figure 3). Temporal differences in well 0618 profiles are also apparent for SC, which varied more with depth in September 2013 than in subsequent profiles (in April 2014 and October 2015) (Figure 44).[11]

As shown in Figure 53, except for calcium, vertical profile shapes for most remaining major ions are similar to that measured for SC. This is also the case for DOC and TOC. Apart from pH and calcium (which had randomly varying profiles), iron (mostly not detected), and nitrate, most variables appear to be strongly correlated. This conclusion is supported by the corresponding correlation matrix or heatmap discussed later in this section (Section 5.5, Figure 61). In this well, uranium is strongly and positively correlated with SC ($r = 0.97$) and all major ions except calcium ($r \geq 0.91$).

[11] The profile results from May and October 2012 and February 2013, illustrated in Figure 3 and used to describe the catalyst for the Variation Project, preceded the Phase I and Phase II profiles.

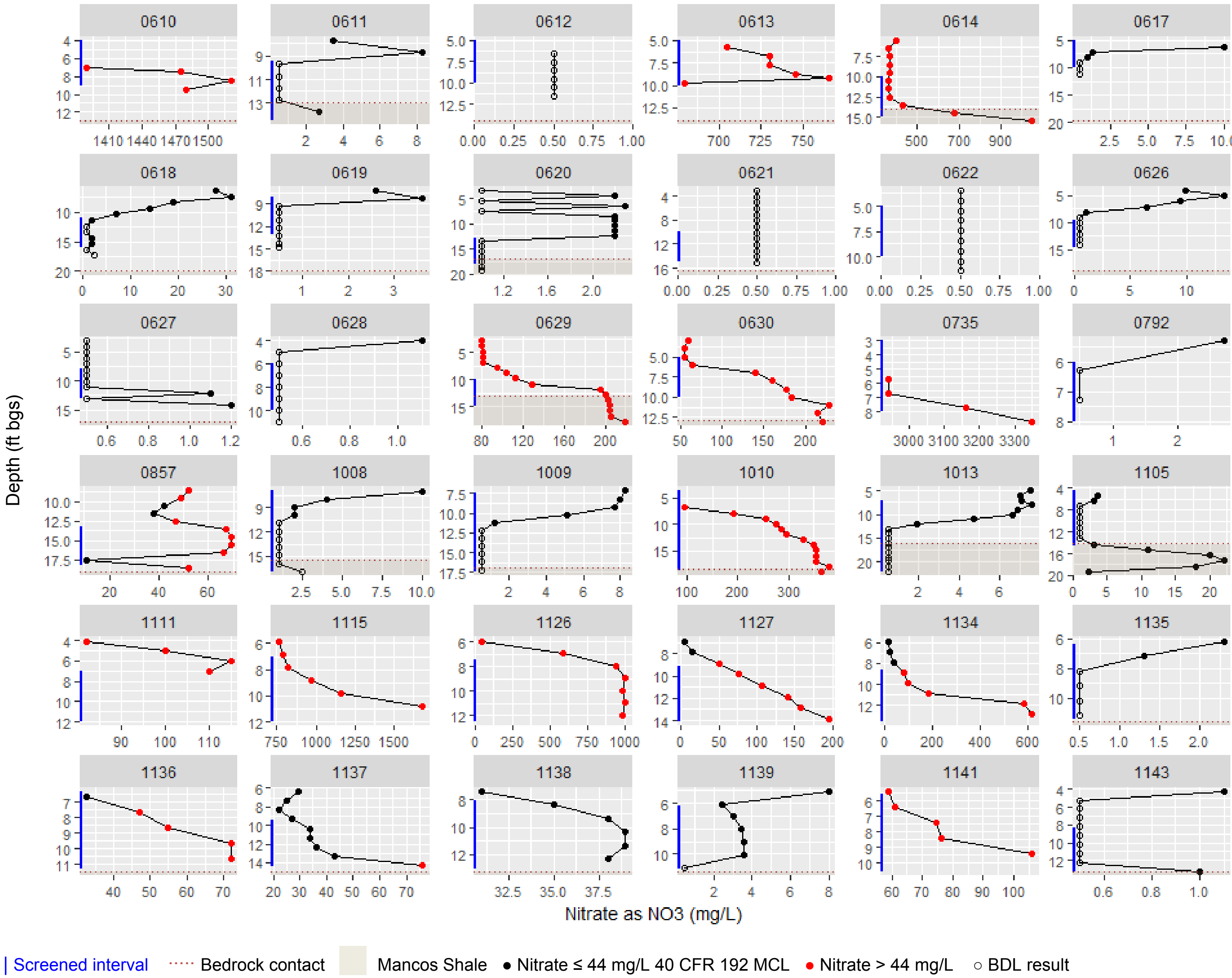
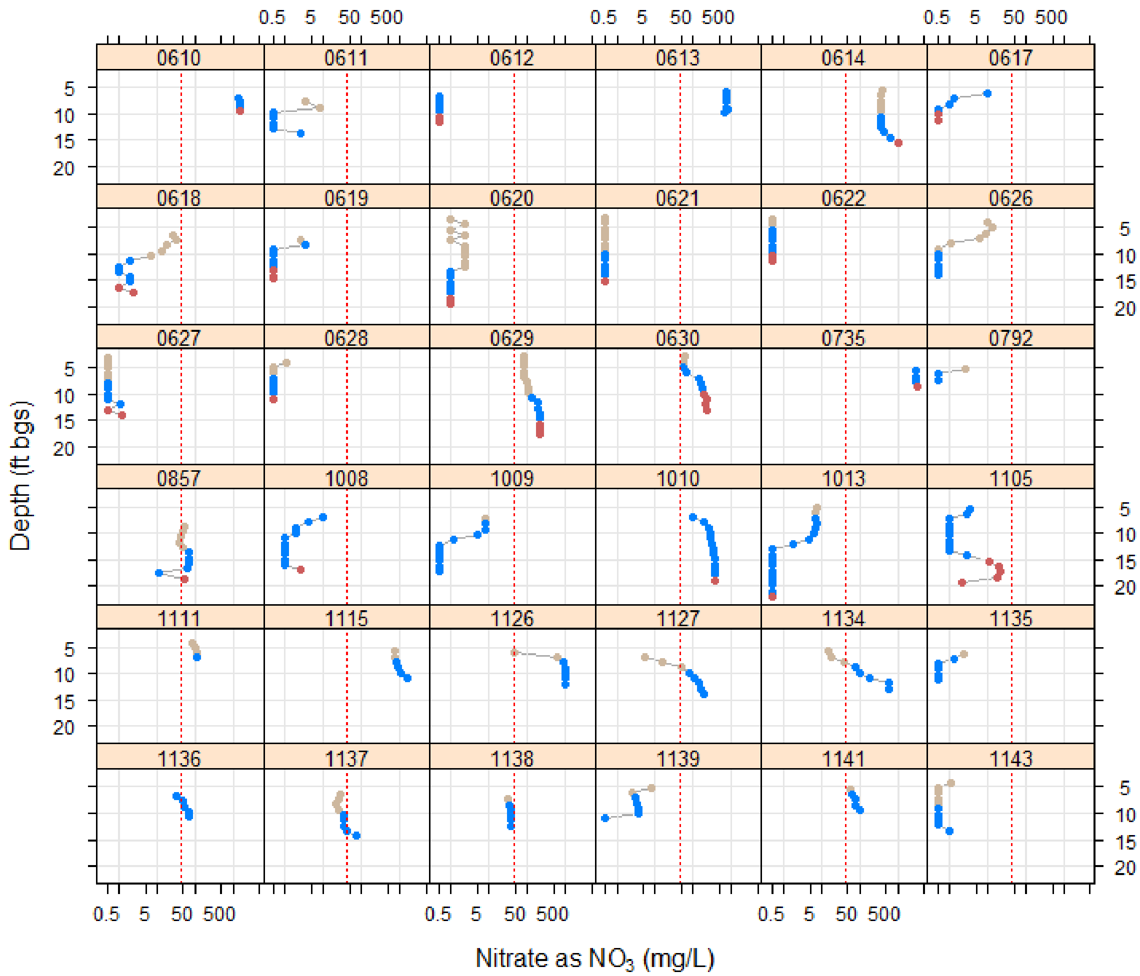


Figure 51. Nitrate as NO_3 Profiles in Shiprock Site Floodplain Wells, October 2015: Unique Scales



Casing

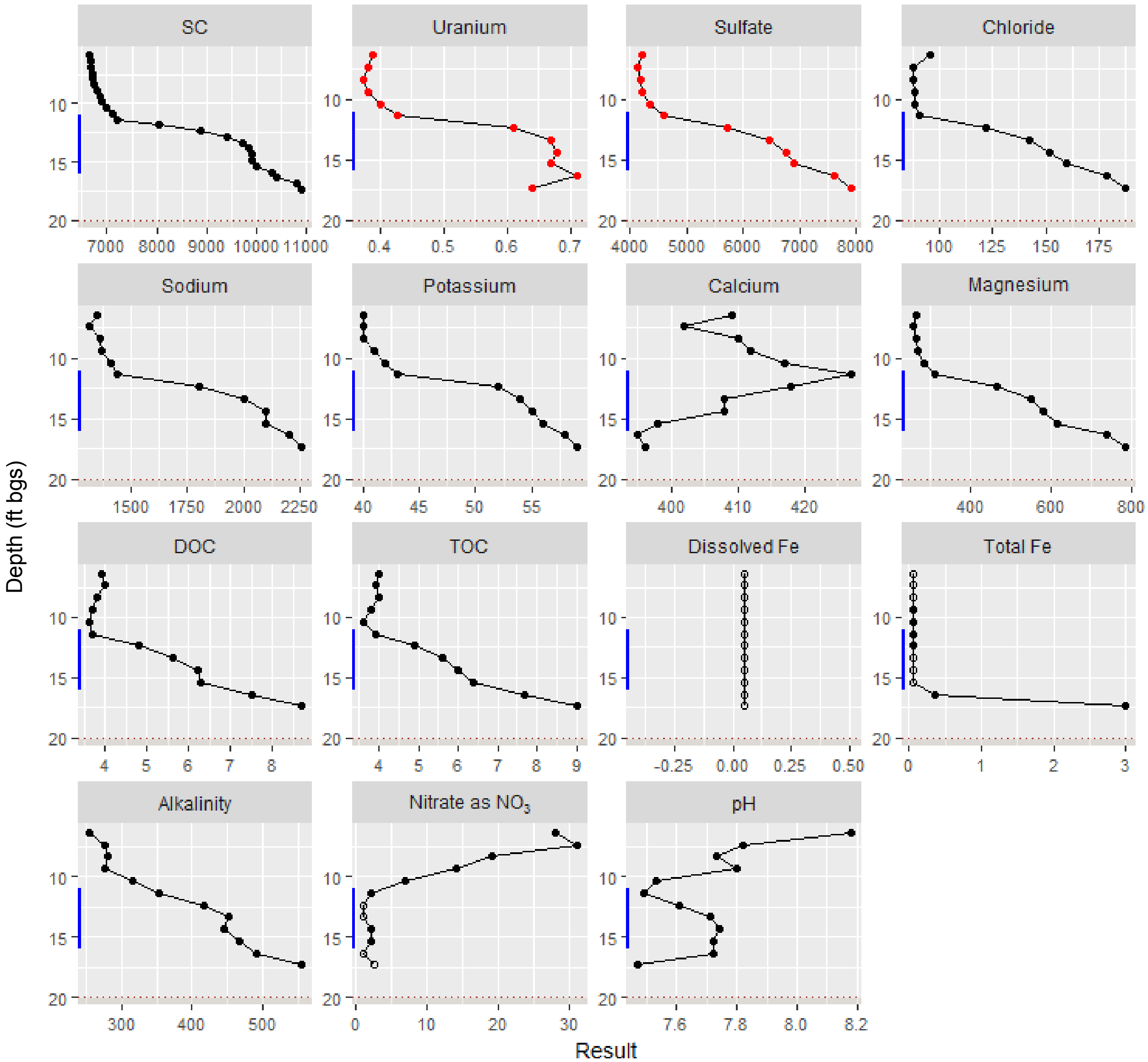
Screen

Sump

--- 44 mg/L 40 CFR 192 MCL (converted from 10 mg/L nitrate as N)

Note: Use of a logarithmic *x*-axis scale may mask the magnitude of change in nitrate concentrations with depth.

Figure 52. Nitrate as NO_3 Profiles in Shiprock Site Floodplain Wells, Common Scales



| Screened interval

····· Bedrock contact   Mancos Shale

● Result exceeds corresponding 40 CFR 192 MCL or background level:
0.044 mg/L uranium, 2000 mg/L sulfate (background); 44 mg/L nitrate as NO_3

○ BDL result

Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Figure 53. Variable Profiles from Shiprock Site Floodplain Well 0618, October 2015 Example of Within-Screen Variation (Group 1)

Another example of a well characterized by within-screen variation is well 0630, located in the western floodplain near the base of the Bob Lee Wash outlet. Figure 54 plots corresponding vertical profile results for all analytes, including ^{222}Rn. Similar to the profiles for well 0618, the similarities in profile shapes across most analytes is striking. SC and analyte concentrations are homogeneous within the upper casing, increase progressively through the 5 ft screen, peak, and then stabilize in the sump. Even nitrate (elevated in this well) increases with depth in a similar manner.

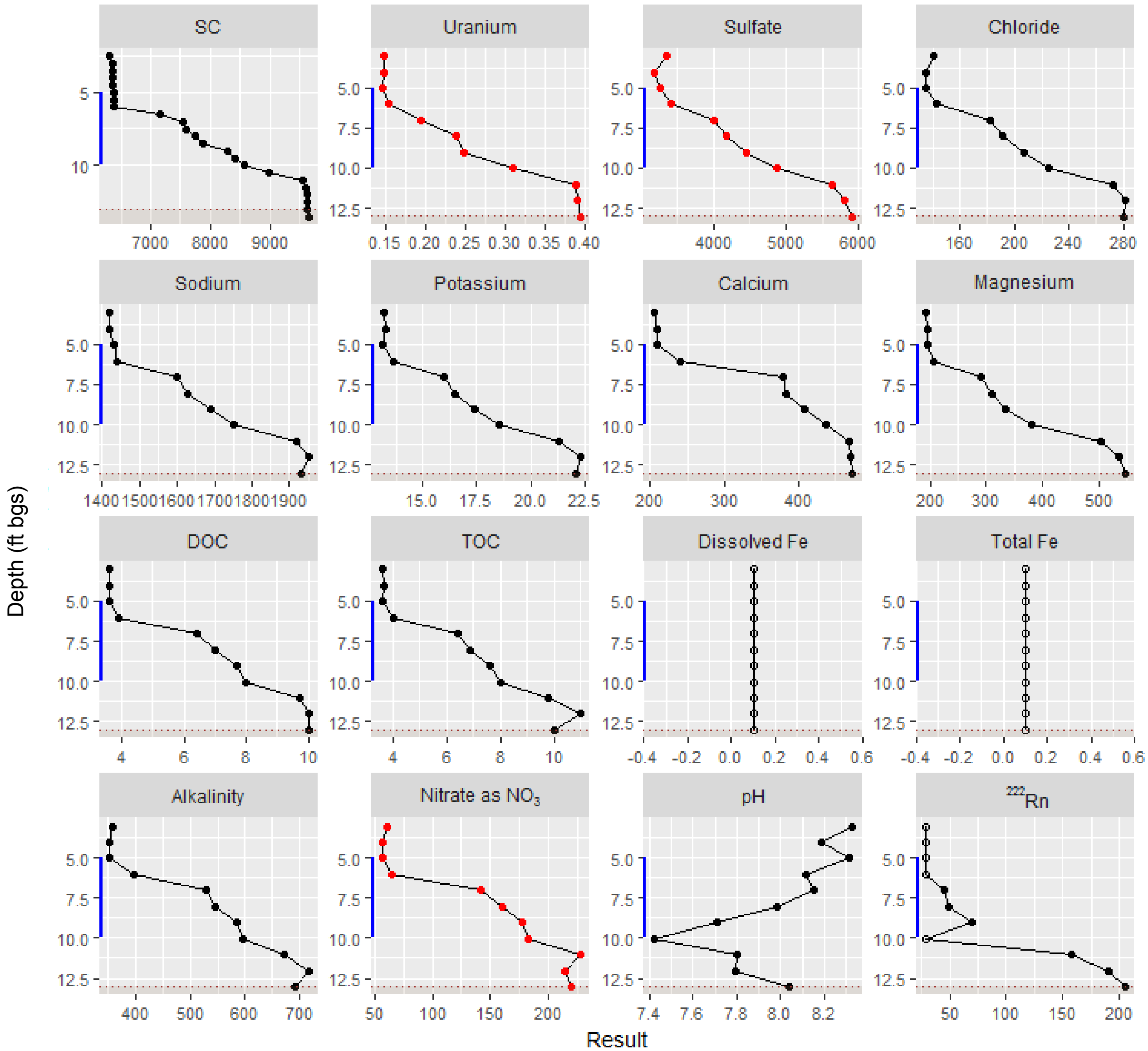
The ^{222}Rn profile is different: levels are low (<29–69 pCi/L) through much of the screened interval (as portrayed), suggesting stagnant conditions in this region. Levels then increase to 158–205 pCi/L in the sump region approaching the Mancos Shale contact. These anomalous ^{222}Rn results, indicating higher flux in the sump than in the screened interval, prompted an examination of the downhole video results.[12] The visual field in this well was obscured and the top of the screen was not visible until 7.2 ft. However, the screen bottom was visible and measured at a depth of 11.8 ft bgs, 1.8 ft below the bottom screen depth indicated in the well log (and LM's database). This discrepancy might explain the anomalous ^{222}Rn results shown in Figure 54.

To illustrate examples of wells representing both within-screen variation (Group 1) and within-screen homogeneity (Group 2), Figure 55 plots vertical profile results for wells 1137, 1138, and 1139. These wells, located in a line between the well 1089/1104 pumping area and the San Juan River, are spaced approximately 50 ft apart (Figure 39).

Vertical profiles for well 1137, closest to the San Juan River, are characterized by within-screen variation. This is evident in Figure 55, which shows a gradual increase in magnitude for most parameters, progressing with depth from the upper casing/screen transition to the sump region overlying the Mancos Shale contact. For example, SC increases gradually from about 6300 µS/cm just above the screened interval to 15,800 µS/cm at the screen/sump contact. The same pattern was found for sulfate and all remaining major ions. Although uranium increased from 0.3 to 1.25 mg/L in the profile, concentrations stabilized at about 1 mg/L in the mid-screen interval.

The only parameters that did not exhibit this gradual increasing trend with depth in well 1137 were iron (total and dissolved), pH, and ^{222}Rn. Radon-222 was not detected in the upper casing and ranged from 72 to 110 pCi/L in the screened zone. Theoretically, these results might suggest relatively low flow (or groundwater flux) in this well. However, in order for ^{222}Rn to be a reliable indicator of groundwater flux, there has to be parent emanation from the aquifer. If, as is probably the case for well 1137 (just 30–40 ft from the San Juan River), there is a constant influx of river water, this could dilute any ^{222}Rn originating in the aquifer.

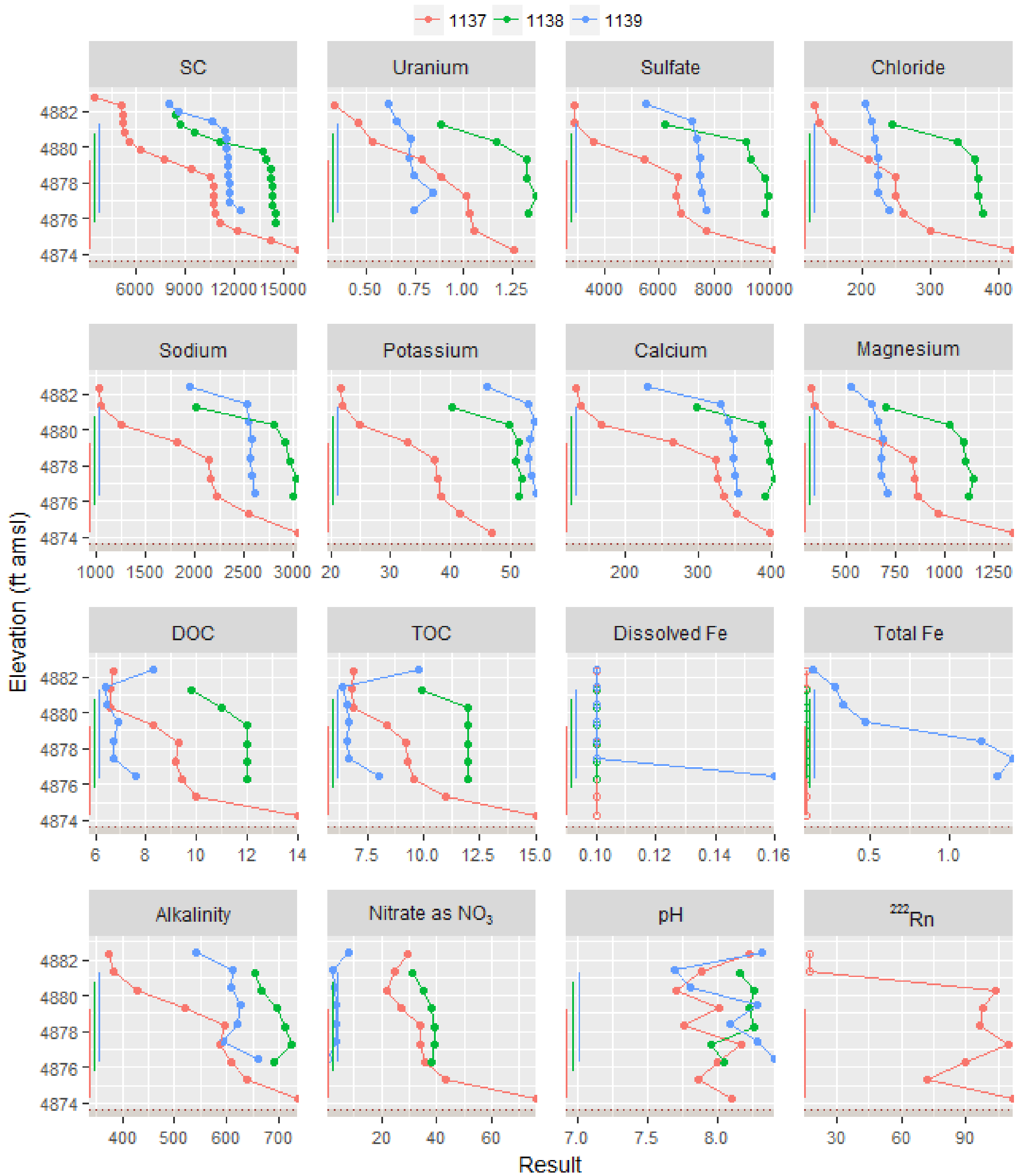
[12] A summary of the downhole video profiles, including identification of discrepancies in screen placements, is provided in Appendix B. In cases where discrepancies were identified (e.g., as found for well 0630), screen interval placements shown in the figures were not changed. Rather, the screen information in LM's database (from the original well log) was used. In these cases, a repeated downhole camera survey is recommended.



| Screened interval (based on well log); downhole video indicated 1.8 ft discrepancy in placement
Bedrock contact
Mancos Shale
● Result exceeds corresponding 40 CFR 192 MCL or background level:
0.044 mg/L uranium, 2000 mg/L sulfate (background); 44 mg/L nitrate as NO_3
○ BDL result

Note:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Figure 54. Variable Profiles from Shiprock Site Floodplain Well 0630, October 2015 Example of Within-Screen Variation, ^{222}Rn Determined



| | | Well screens shown on left *y*-axis, color-coded by well (1137, 1138, 1139)

⋯ Bedrock contact

Mancos Shale

○ BDL result

Note: All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$

Abbreviation:
ft amsl feet above mean sea level

Figure 55. Variable Profiles from Shiprock Site Floodplain Wells 1137, 1138, and 1139, Groups 1 and 2 Within-Screen Variation (Well 1137) and Screen Effect Homogeneity (Wells 1138 and 1139)

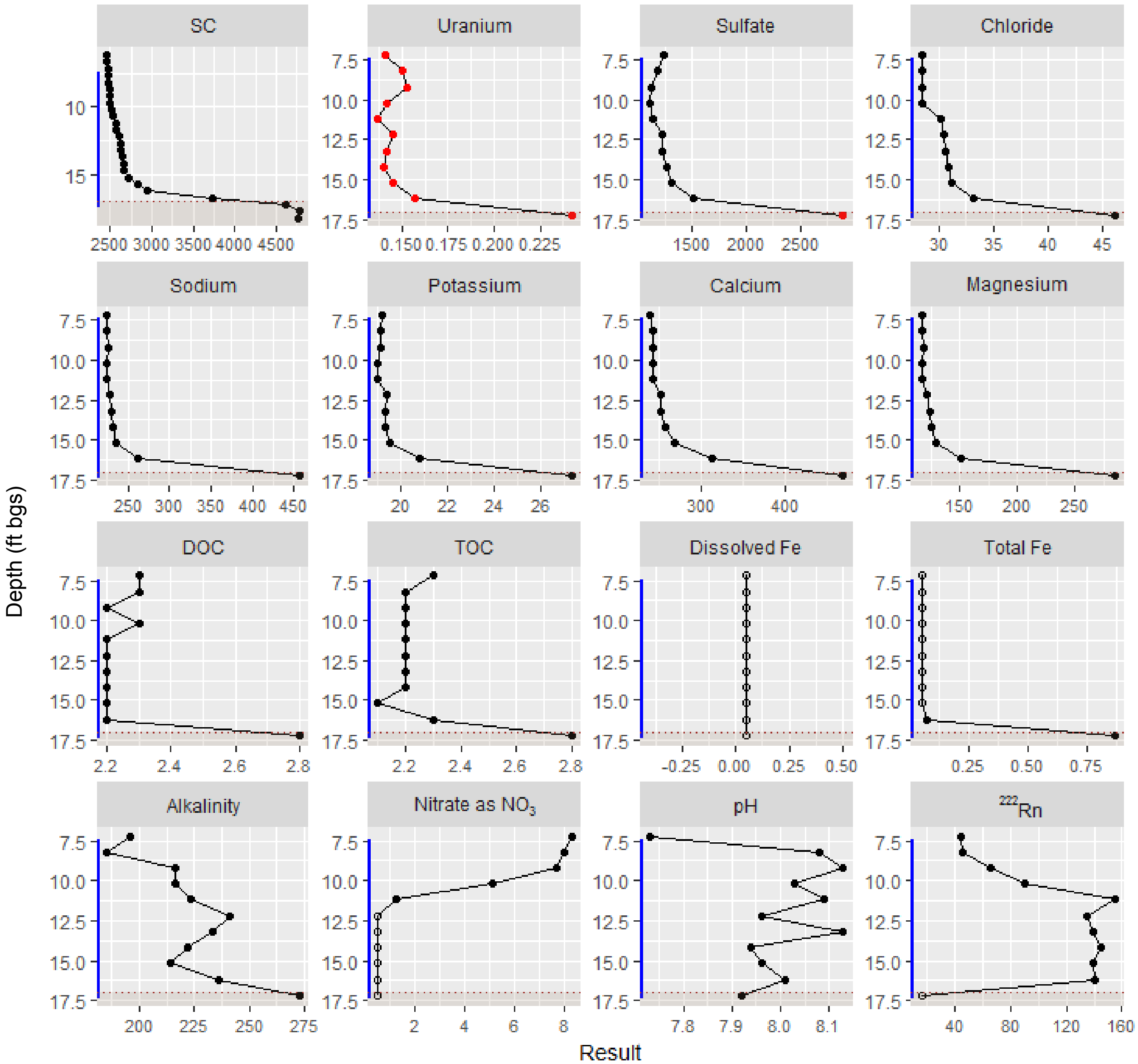
In contrast to observations for well 1137, SC and analyte profiles for wells 1138 and 1139 were for the most part homogenous within the screened interval (Figure 55).[13] These observations are consistent with those made during a similar profiling effort conducted in July 2013. That effort was prompted by observed increases in contaminant (uranium, sulfate, and nitrate) concentrations in several wells near the San Juan River (0857, 1136, 1137, 1138, and 1139). That investigation differed, however, in that SC and contaminant profiles were taken both before and after well development. For the subset of wells evaluated, stratification (in both SC and chemical measurements) was most pronounced in wells 0857 and 1136. Little stratification was measured in wells 1138 and 1139. Additionally, there were no consistent differences in pre- versus post-development profiles for this well subset. Methods and results of this study are documented in Appendix F and in SN3 (2013). The reason for the comparatively higher degree of stratification in SC and other parameters in well 1137 (nearest the river) versus that found for nearby wells 1138 and 1139 is not known at this time.

A classic example of a well characterized by dead-zone variation (Group 3) is shown in Figure 56, which plots vertical profile results for well 1009, installed about 300 ft east of Trench 1. In this well, levels of most parameters (e.g., SC, uranium, sulfate, and other ions) are consistent in the screened interval, but then increase (approximately double) near the bottom screen/sump transition corresponding to the Mancos Shale (bedrock) contact.

For example, SC averages about 2500–2600 µS/cm in the upper and middle screen portion of well 1009, but then increases near the screen/sump transition to a maximum of 4790 mg/L in the sump. The uranium profile is similar—concentrations are relatively stable at 0.14–0.15 mg/L in the upper and mid-screen portion of the well, but then increase to 0.24 mg/L at the bottom screen portion. Sulfate concentrations are about 1100–1200 mg/L through most of the screened interval, but increase to 2900 mg/L at the bottom of the screen near the sump. Similar patterns were found for the remaining major ions, DOC, and TOC.

In contrast to the prevailing increasing trend towards the sump region in well 1009 (Figure 56), nitrate concentrations decrease from about 8 mg/L in the uppermost samples of the screened interval to levels below detection limits at the mid-screen interval. The ^{222}Rn profile suggests relatively high groundwater flux through this mid-screen portion (155 pCi/L) but more stagnant conditions in the portion of the well where nitrate was detected and in the sump. The nitrate concentration in well 1009 decreased from more than 900 mg/L NO_3 to less than 1 mg/L from 2000 to 2010. Decreasing nitrate concentrations in groundwater can result from microbial reduction. However, the decreasing nitrate concentrations in this well over this 10-year period correlate positively with decreasing chloride concentrations and with many other dissolved species (including sulfate and uranium). Since chloride is not responsive to microbial reduction, it is likely that the temporal variation in nitrate concentration is related to some other process (e.g., varying groundwater flow patterns). Although the smaller change in nitrate concentration in the vertical profile (from 8 to <0.5 mg/L) may be related to redox reactions, the trend from higher nitrate in the more stagnant zone to lower nitrate in the higher flow zone (based on ^{222}Rn measurements) seems to refute this process.

[13] Wells 1138 and 1139 are two of the three wells characterized by within-screen homogeneity (Group 2), as indicated in Tables 6 and 7. The only other well in this group was well 1126, in the Trench 2 area.



| Screened interval
⋯ Bedrock contact
Mancos Shale
● Result exceeds corresponding 40 CFR 192 MCL or site standard

- 0.044 mg/L uranium
- 2000 mg/L sulfate
- 44 mg/L nitrate as NO_3

○ BDL result

Note:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Figure 56. Variable Profiles from Shiprock Site Floodplain Well 1009, October 2015 Group 3, Example of Dead-Zone Variation, ^{222}Rn Determined

As documented in site monitoring reports (e.g., DOE 2018a), concentrations of uranium, sulfate, nitrate have decreased markedly in well 1009 since about 2008 (sulfate and nitrate levels are now below corresponding standards). Whether or not the observed increases in the sump region of this well has affected interpretations of routine monitoring results is not known. This issue is discussed later in this section (Section 5.6).

A final example of a Shiprock site floodplain well profile, this time representing Group 4 (with no consistent pattern)—is shown in Figure 57 for well 0626. The SC profile for this well, located in the western floodplain (Figure 39), is characterized by both within-screen and dead-zone variation. SC is relatively stable (about 4300 µS/cm) in the uppermost two-thirds of the well screen, but then increases to 5700 µS/cm in the bottom screen portion and sump. The April 2016 downhole video showed that the well screen, although clean, was about 1.3 to 1.6 ft higher than the placement indicated by the well construction record. If this is the case, the higher SC measurements correspond to the sump region of the well.

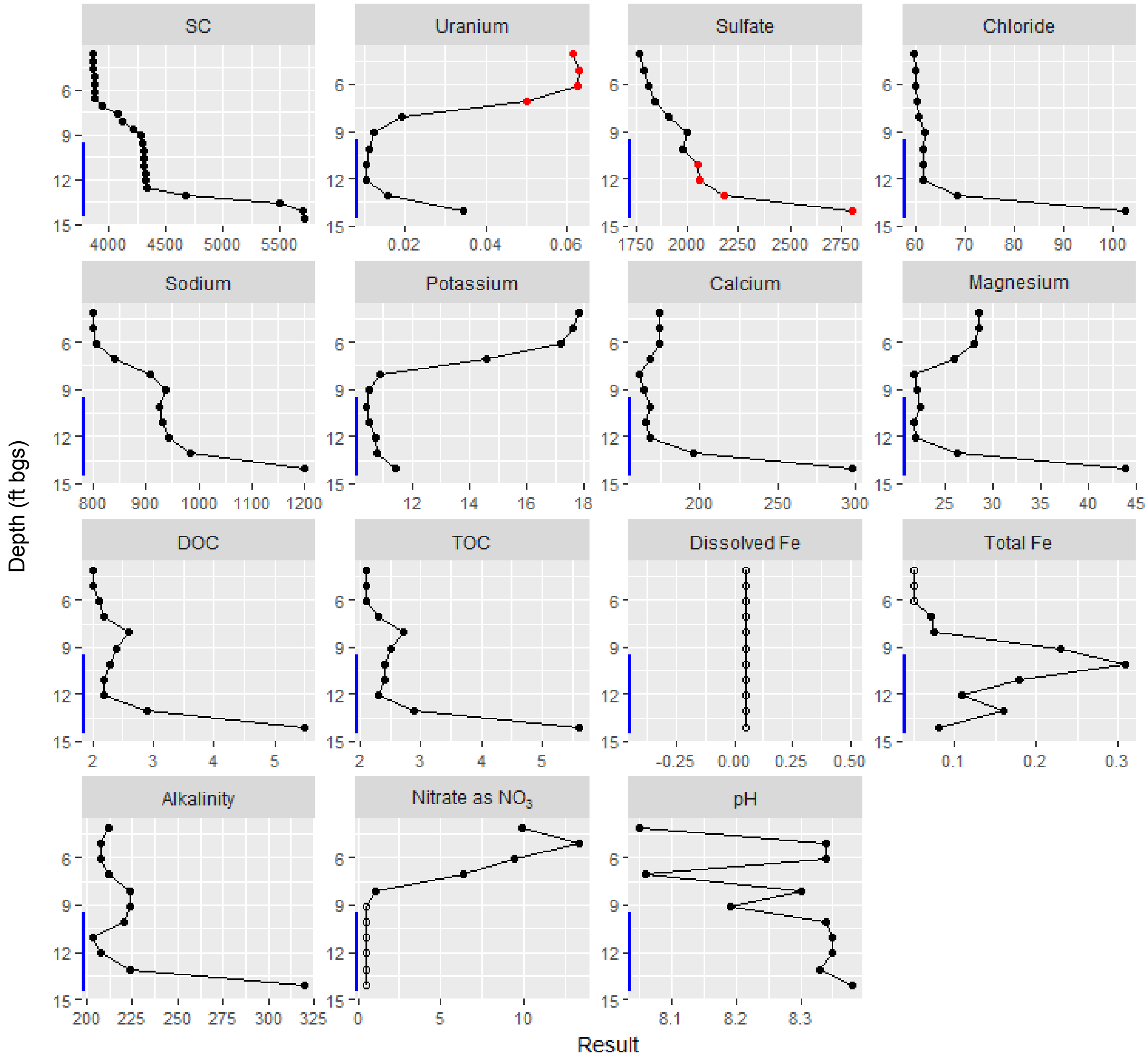
While sulfate and most major ion profiles are similar to the SC profile, those for uranium and nitrate are markedly different. Uranium concentrations are highest (0.05–0.06 mg/L) in the upper casing, then decrease to 0.01–0.02 mg/L within the screened interval. Even if the apparent discrepancy in screen placement is accounted for, the highest concentrations still correspond to the uppermost non-screened interval. The nitrate profile for this well shows a similar decrease with depth and homogenously low levels within the screen. Reasons for these unusual signatures are not known. Subsequent ^{222}Rn determinations and a repeated downhole video camera profile are recommended because they might elucidate factors accounting for the anomalous uranium and nitrate profiles.

In this section, only seven of the 36 profiles for Shiprock site floodplain wells—representing each of the four profile categories—have been discussed. Even in this small subset, the marked variation in SC and contaminant profiles is apparent, as is the agreement between SC and many parameters (except for the Group 4 category of wells). Before presenting a more detailed examination of pairwise correlations (Section 5.5), this section concludes with a summary of results for the ten ^{222}Rn profiles determined for this site.

<u>Radon-222 Profiles</u>

Radon-222 profiles have already been discussed for three of the wells selected to represent different profile categories: 0630 (Figure 54), 1137 (Figure 55), and 1009 (Figure 56). The following paragraphs summarize these findings, along with the results of the remaining seven ^{222}Rn profiles for Shiprock site wells. Corresponding results are illustrated in Figure 58.

Well 0614 had the lowest ^{222}Rn concentrations, ≤ 27 pCi/L throughout the profile, suggesting very limited flow of groundwater through the well. A downhole video showed that the well screen of well 0614 was one of the cleanest recorded and was correctly located at the depth indicated by the well construction record. A possible explanation for the low ^{222}Rn level may be that the screen is located in a low hydraulic conductivity portion of the aquifer, or the well filter pack is fouled.



| Screened interval

····· Bedrock contact

Mancos Shale

● Result exceeds corresponding 40 CFR 192 MCL or background level:
0.044 mg/L uranium, 2000 mg/L sulfate (background); 44 mg/L nitrate as NO_3

○ BDL result

Note:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$,

Figure 57. Variable Profiles from Shiprock Site Floodplain Well 0626, October 2015: Group 4 Example No Consistent Pattern in Profiles

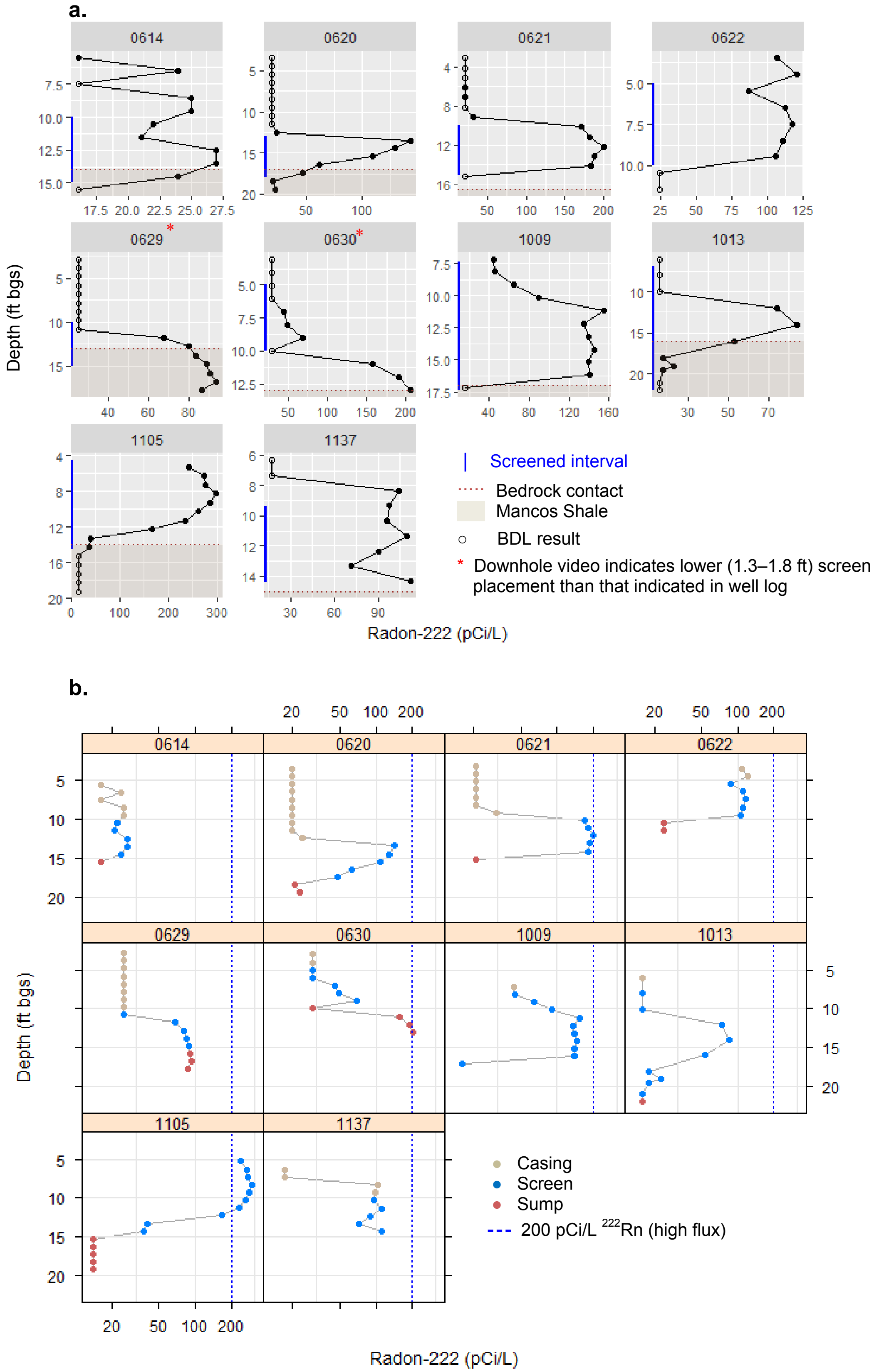


Figure 58. Radon-222 Profiles from Shiprock Site Floodplain Wells, October 2015
(a) Unique scales and Mancos Shale contact shown;
(b) Common scales

Wells 0620, 0621, and 0622 were installed in a line and spaced only about 10 ft apart (Figure 39). The well with the deepest screen (well 0620) had its peak ^{222}Rn concentration (142 pCi/L) at the top of the screen, followed by a gradual decreasing trend to the bottom of the screen. Radon-222 concentrations in the upper and lower cased zones were low, indicating stagnation outside the well screen zone. Well 0621 had a similar ^{222}Rn profile: relatively high concentrations (100–125 pCi/L) through the screened interval versus low (mostly nondetect) concentrations in the upper casing and sump. This well (0621) is considered to have a classic ^{222}Rn concentration profile characteristic of groundwater flowing through the screened zone.

Well 0622, with the shallowest screened zone, had ^{222}Rn between 87 and 121 pCi/L in all but the two samples in the sump. Two samples collected above the well screen also had relatively high ^{222}Rn concentrations. There are three potential causes of the anomalously high values in the upper casing in well 0622: (1) vertical upward flow (mixing) in the wellbore; (2) disruption of groundwater in the wellbore during sampling; or (3) misplacement of the well screen. The first possibility (upward flow) is the most likely because many other wells were sampled without noticeable disruption of the water column, and a downhole video indicates that the placing of the screen is correct.

Both wells 0629 and 0630 have seemingly anomalous ^{222}Rn profiles in that concentrations are highest in the sump portion of the well. In well 0629, this region penetrates the Mancos Shale. As discussed previously for well 0630, these anomalies may be explained by the downhole video profiles, which suggest discrepancies of about 1.3 to 1.8 ft in screen placement relative to the well construction log. In both cases, screens are apparently lower than the depths indicated in corresponding well logs. During downhole camera surveys, the image was obscured in both wells (Appendix B, Table B.2.3), so a repeated camera survey may be warranted. Well 0629 is not routinely sampled, but well 0630 is (in which case, well redevelopment may also be warranted).

As discussed previously, well 1009 appears to have groundwater flowing through most of the screened zone, as indicated by relatively high ^{222}Rn concentrations (about 150 pCi/L). In contrast, many of the samples collected from well 1013 had ^{222}Rn concentrations near or less than the detection limit, indicating limited flow overall. Some water appears to be flowing through a small zone in the middle of the screen, however, as indicated by ^{222}Rn between 52 and 84 pCi/L.

Well 1105 had the highest ^{222}Rn concentrations determined in the Shiprock site floodplain well profiles—with 167 to about 300 pCi/L through most of the 10 ft screened zone, indicating high groundwater flux in this region. Concentrations then decreased to less than detection limits in the sump, an example of a classic ^{222}Rn profile.

As discussed previously, ^{222}Rn concentrations in well 1137 were relatively low and variable in the screened zone and were not detected in the two uppermost samples taken from the upper casing. Although these results might suggest relatively low flow in this well, they might also reflect influx of water from the adjacent San Juan River, which could dilute ^{222}Rn originating in the aquifer.

5.5 Assessment of Correlations: Pairwise Comparisons

As was done for the Durango sites (e.g., Section 4.2.3), scatterplot matrices were generated to visualize and quantify the pairwise relationships among the 15–16 variables measured during the Phase II study for Shiprock site floodplain wells. Figure 59 illustrates these relationships using the combined data set for all 36 wells and all well intervals—the upper casing (n = 92), screen (n = 197), and sump (n = 36). All variables are included in this matrix except for dissolved iron, which was not detected in most wells.

Because data from numerous wells—each different with respect to the corresponding combined analyte profile signature, contaminant magnitude, or level of variation—were lumped, this figure is intended only as an introductory overview. When using this combined data set, strong correlations (e.g., $r \geq 0.9$) are considered significant.[14] As discussed below, moderate correlations quantified for the combined data set (e.g., $0.65 < r < 0.8$) do not necessarily indicate that this moderate correlation applies to individual wells.

In general, based on the lumped data set for all Shiprock site wells, SC is most strongly correlated with sulfate (r = 0.96) and sodium (r = 0.93). There is a moderate association between SC and uranium (r = 0.75). This moderate correlation between SC and uranium may be attributable to outlier data from the following wells:

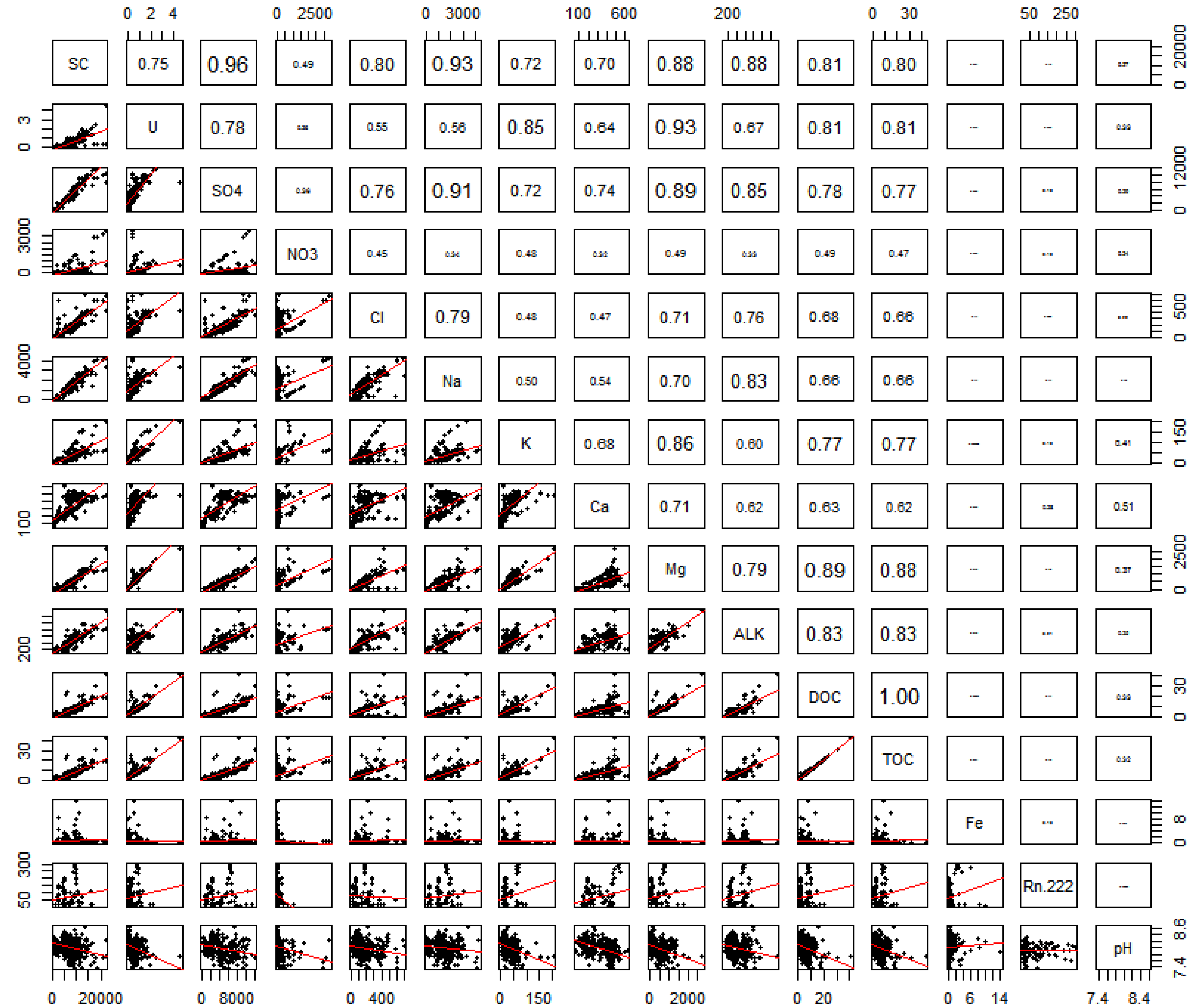
- 0613, with the highest uranium in the data set (1.4–4.6 mg/L); and
- 0735, with the highest SC (17,100–22,000 µS/cm).

If these outliers are removed, the correlation between SC and uranium is stronger (r = 0.81).

The strong correlations between SC, sulfate, and sodium were discussed earlier. Apart from these variable pairs and the perfect correlation between DOC and TOC (r = 1), remaining pairwise associations in Figure 59 are not noteworthy. For these remaining pairs, the relatively poor correlation may be due to outlier points (e.g., extremes such as uranium in well 0613). More likely, these relatively weaker correlations reflect the lumping of data from wells with no consistent pattern in the profiles (Group 4 wells) or combining data from the casing, screen, and sump. Certain variables—most notably total iron and pH—can be excluded from further discussion and subsequent figures, given consistently weak associations with most parameters ($r < 0.45$, not discernible in most panels in Figure 59).

To refine this evaluation, pairwise correlations are examined further—first by profile category, and then on an individual well basis (for SC versus uranium). Figure 60 shows the scatterplot matrix for Group 1 wells (defined in Table 6): those with SC and analyte profiles characterized as having predominantly within-screen variation. In this case, because of the category definition (within-screen variation), the data are limited to within-screen measurements only. Data from well 0613 are also excluded, given the outliers mentioned previously.

[14] Apart from the extremes of the range—r = 1 or −1 (perfect linear relationship) and r = 0 (no linear relationship)—there is no clear cutoff or value that signifies a strong, moderate, or weak correlation. These determinations are somewhat subjective and are based on an examination of the distribution of the data and the degree of scatter about the regression line. It is also necessary to assess the potential for any extremes in the data set (e.g., very high or low values of a variable result that affect the slope of the regression line). In some cases, extremes can yield an artificially high correlation coefficient.



Lower-left triangle: pairwise scatterplots, where — is linear trend line.
Upper-right triangle: Corresponding correlation coefficients for each variable pair (defined below)

0.96 Absolute value of Pearson's product-moment correlation coefficient, or *r*. Font size proportional to magnitude of *r*.

Note:
Scatterplot generated using the pairs() function from R's base graphics, R version 3.4.2 (R Core Team 2017).
Scales shown on *x*- and *y*- axes of figure.
All units in mg/L except SC (μS/cm), ^{222}Rn (pCi/L), and pH.

Abbreviations
ALK = alkalinity (as $CaCO_3$); Ca = calcium; Cl = chloride; K = potassium; Mg = magnesium; Na = sodium; NO3 = nitrate (as NO_3); Rn.222 = ^{222}Rn; SO_4 = sulfate; U = uranium.

Figure 59. Scatterplot Matrix of Variables in All Shiprock Wells Combined, All Intervals (Casing, Screen, and Sump)

As shown in Figure 60, the SC signatures for the combined Group 1 (within-screen variation) data set are best explained by sulfate ($r = 0.96$) and magnesium ($r = 0.92$). There is a fairly strong linear correlation between SC and uranium ($r = 0.86$), with relatively little scatter about the regression line. For this well subset, many other variable pairs appear to have a fairly strong linear relationship, including:

- SC and DOC, $r = 0.90$
- Uranium and magnesium, $r = 0.95$
- Sulfate and sodium, $r = 0.95$
- Magnesium and DOC, $r = 0.93$

Although ^{222}Rn was analyzed in only 10 of the 36 wells, there is also a fairly strong association between this parameter and DOC ($r = 0.86$), sulfate ($r = 0.80$), and uranium ($r = 0.79$).

An example of the strong associations found in a single well is provided in the correlation matrix heatmap shown in Figure 61 for well 0618. As discussed in the introduction (Figure 3), initial observations of stratification in this well were a catalyst for this study. For most parameters, the variation occurs predominantly within the screened interval. As shown below, uranium is strongly and positively correlated with SC ($r = 0.97$) and all major anions and cations except calcium ($r \geq 0.91$).

Scatterplot matrices were not developed for wells in Group 2 (within-screen homogeneity) because only three wells comprise this group: 1126, 1138, and 1139. However, associations between SC and uranium for these wells are plotted and discussed later in this section.

Figure 62 shows the pairwise correlation matrix for Group 3 wells, characterized by increases in SC and other analyte concentrations at the bottom screen / sump transition. Only data from the screened interval and sump are included. This figure illustrates the same general trend noted previously for both the lumped data set (Figure 59) and Group 1 wells (Figure 60): a strong positive linear association between SC and sulfate ($r = 0.97$). The association between SC and uranium is weaker, however ($r = 0.75$), and there is notable scatter about the regression line. This well subset differs from others examined in this section in that uranium is correlated with both nitrate and magnesium in this subset of wells ($r = 0.94$ and 0.95, respectively). In the corresponding scatterplots (column 2, rows 4 and 7), there is little scatter about the regression line.

Scatterplot matrices were not developed for the combined Group 4 data set because, as reflected in the category definition (Table 6), there was no consistent pattern in the profiles. Correlations for this well subset are examined on an individual basis for SC versus uranium as discussed below. The preceding scatterplot matrices are useful for identifying consistent associations between parameters (e.g., SC and sulfate). However, because a major objective of this report is to evaluate the potential for using SC as an indicator of uranium concentrations, examination of correlations on an individual well basis is also warranted.

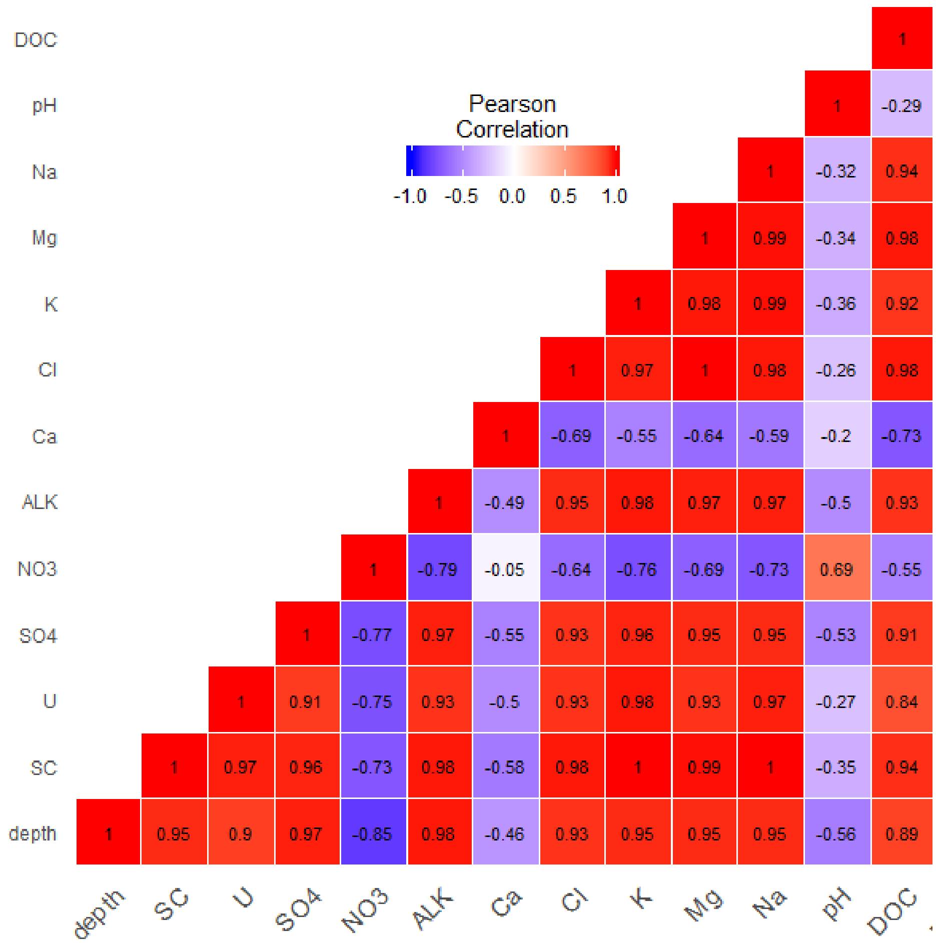
Lower-left triangle: pairwise scatterplots, where — is linear trend line.
Upper-right triangle: Corresponding correlation coefficients for each variable pair (defined below)
0.96 Absolute value of Pearson's product-moment correlation coefficient, or *r*.
Font size proportional to magnitude of *r*.

Notes:
Scatterplot generated using the pairs() function from R's base graphics, R version 3.4.2 (R Core Team 2017).
Scales are shown on *x*- and *y*- axes of figure.
Data from well 0613 excluded given extreme (outlier) uranium concentrations (1.4–4.6 mg/L).
All units in mg/L except and SC (µS/cm) and ^{222}Rn (pCi/L).
pH and total iron are excluded given weak associations with most parameters.
Dissolved iron is excluded as it was not detected in most Shiprock site samples.
TOC is excluded as this parameter is redundant (highly correlated) with DOC.

Abbreviations:
ALK = alkalinity (as $CaCO_3$); Ca = calcium; Cl = chloride; K = potassium; Mg = magnesium; Na = sodium; NO3 = nitrate (as NO_3); Rn.222 = radon-222; SO4 = sulfate; U = uranium.

Figure 60. Scatterplot Matrix for Shiprock Site Group 1 Wells, Within-Screen Variation

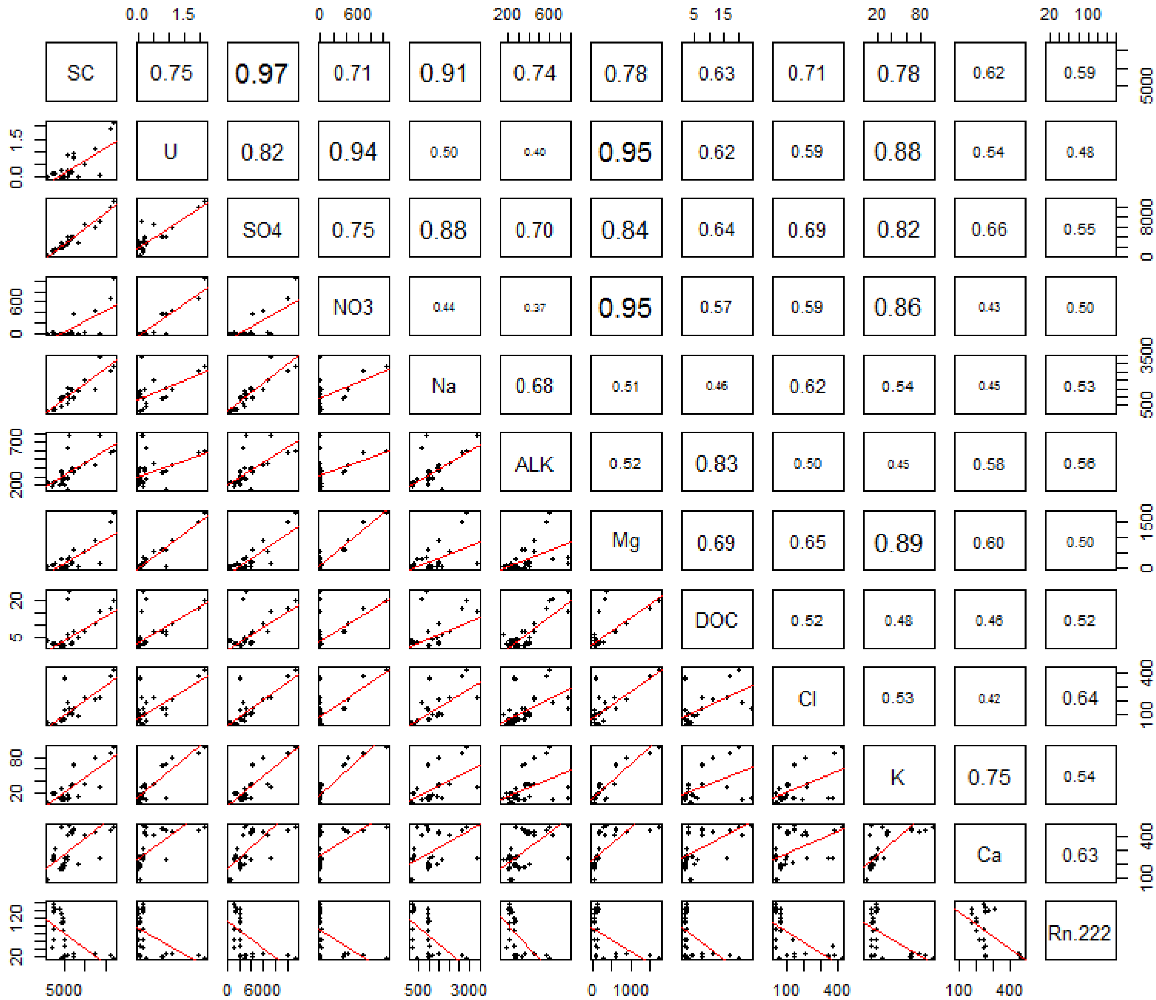
Wells 0610, 0617, 0618, 0629, 0630, 0792, 0857, 1010, 1115, 1127, 1134, 1136, 1137, and 1141: Screened Interval Only



Notes:
In this correlation heatmap, variable pairs with positive associations ($r > 0$) are shaded in red.
Those with negative associations ($r < 0$) are shaded in blue. The stronger the association, the darker the color.
Unlike other scatterplots provided in this report, depth is also included as a variable. The *r* values in the bottom row of this matrix indicate the extent to which concentrations of most parameters are strongly correlated with depth.
Total and dissolved iron are excluded from this plot as most results were below detection limits
TOC is not shown because it is redundant with DOC (i.e., $r = 1$ for the DOC-TOC pairwise comparison).
All units in mg/L except SC (µS/cm) and pH.

Abbreviations:
ALK = alkalinity (as $CaCO_3$); Ca = calcium; Cl = chloride; K = potassium; Mg = magnesium; Na = sodium; NO3 = nitrate (as NO_3); SO4 = sulfate; U = uranium.

Figure 61. Heatmap for Well 0618 Showing Strong Correlations Between Variables Within-Screen Variation (Group 1)



Lower-left triangle: pairwise scatterplots, where — is linear trend line.
Upper-right triangle: Corresponding correlation coefficients for each variable pair (defined below)
0.97 Absolute value of Pearson's product-moment correlation coefficient, or *r*.
Font size proportional to magnitude of *r*.

Notes:
Scatterplot generated using the pairs() function from R's base graphics, R version 3.4.2 (R Core Team 2017).
Scales are shown on *x*- and *y*- axes of figure.
All units in mg/L except and SC (μS/cm) and ^{222}Rn (pCi/L).
pH and total iron are excluded given weak associations with most parameters.
Dissolved iron is excluded as it was not detected in most Shiprock site samples.
TOC is excluded as this parameter is redundant with DOC.

Abbreviations:
ALK = alkalinity (as $CaCO_3$); Ca = calcium; Cl = chloride; K = potassium; Mg = magnesium; Na = sodium; NO3 = nitrate (as NO_3); Rn.222 = radon-222; SO4 = sulfate; U = uranium.

Figure 62. Scatterplot Matrix for Group 3 Wells, Dead-Zone Variation

Figure 63 plots SC versus uranium (as measured in the vertical profiles) for all Shiprock site floodplain wells profiled in Phase II. To facilitate review, panels are ordered by well consistent with previous plots (e.g., Figures 44 through 52). Because of small sample sizes and uncertainties regarding screen interval depths in some wells, data from all well intervals (even upper casing measurements) are plotted.[15] Points are color-coded according to the corresponding interval (● upper casing, ● screen, and ● sump). As shown in this figure and summarized below, for most of the wells (about 72%), the corresponding r^2 values indicate fairly strong correlations between SC and uranium ($r^2 > 0.75$):

- 14 (39%) of the 36 wells profiled have $r^2 > 0.9$ (corresponding to $r > 0.95$)
- 12 (33%) of the 36 wells profiled have r^2 between 0.75 and 0.9 ($0.87 < r < 0.95$)
- 3 (8%) of the wells have r^2 between 0.5 and 0.75 ($0.71 < r < 0.87$)
- 7 (19%) of the wells have low r^2 (<0.5) (all but one of these wells fell into the Group 4 (random variation) category)

The overall high r^2 values yielded for this data set do not necessarily imply that the linear model is a good fit for all wells. As true for any correlation or regression analysis, the data must be examined further. As shown in Figure 63, upper casing or sump measurements appear to skew the trendline in some cases. For example, higher uranium concentrations in the upper casing in wells 0626 and 1143 yield negative slopes. In well 1008, the extremely high SC (9828 µS/cm) and uranium (0.49 mg/L) measurements in the sump compared to the rest of the well measurements result in an artificially high correlation ($r^2 = 0.99$). To examine the potential influence of these extreme values, Figure 64 plots the same data but using measurements from the screened interval only.

Comparison of the plots in Figure 63 (all profile data) with Figure 64 (screen interval only) demonstrates how, in some cases, extreme values can influence the slope of the regression line and the strength of the correlation. Whereas slopes were negative for wells 0626 and 1143 using all data, plotting just screen interval measurements yielded a positive slope. Whereas the r^2 for well 1008 was initially high ($r^2 = 0.99$), exclusion of the single sump sample yielded an r^2 of 0.3.

The following additional caveat is warranted when interpreting the linear associations and corresponding r^2 values shown in Figures 63 and 64: the small sample sizes are potentially problematic from a theoretical statistical perspective. This caveat applies to the combined data set (Figure 63, where $n < 10$ for most wells), but in particular to the screened interval subset (Figure 64), with an average sample size of 5. In well 1111, only one sample was collected within the screened interval (thus $r^2 = 0$). For the remaining 35 wells, limiting the analysis to screened interval measurements still indicates generally good agreement between SC and uranium in most Shiprock site floodplain wells:

- 14 (40%) of the wells have $r^2 > 0.9$
- 9 (26%) of the have r^2 between 0.75 and 0.9
- 3 (8.6%) of the wells have r^2 between 0.5 and 0.75
- 9 (26%) of the wells have r^2 <0.5 (well 1111 excluded given $n = 1$)

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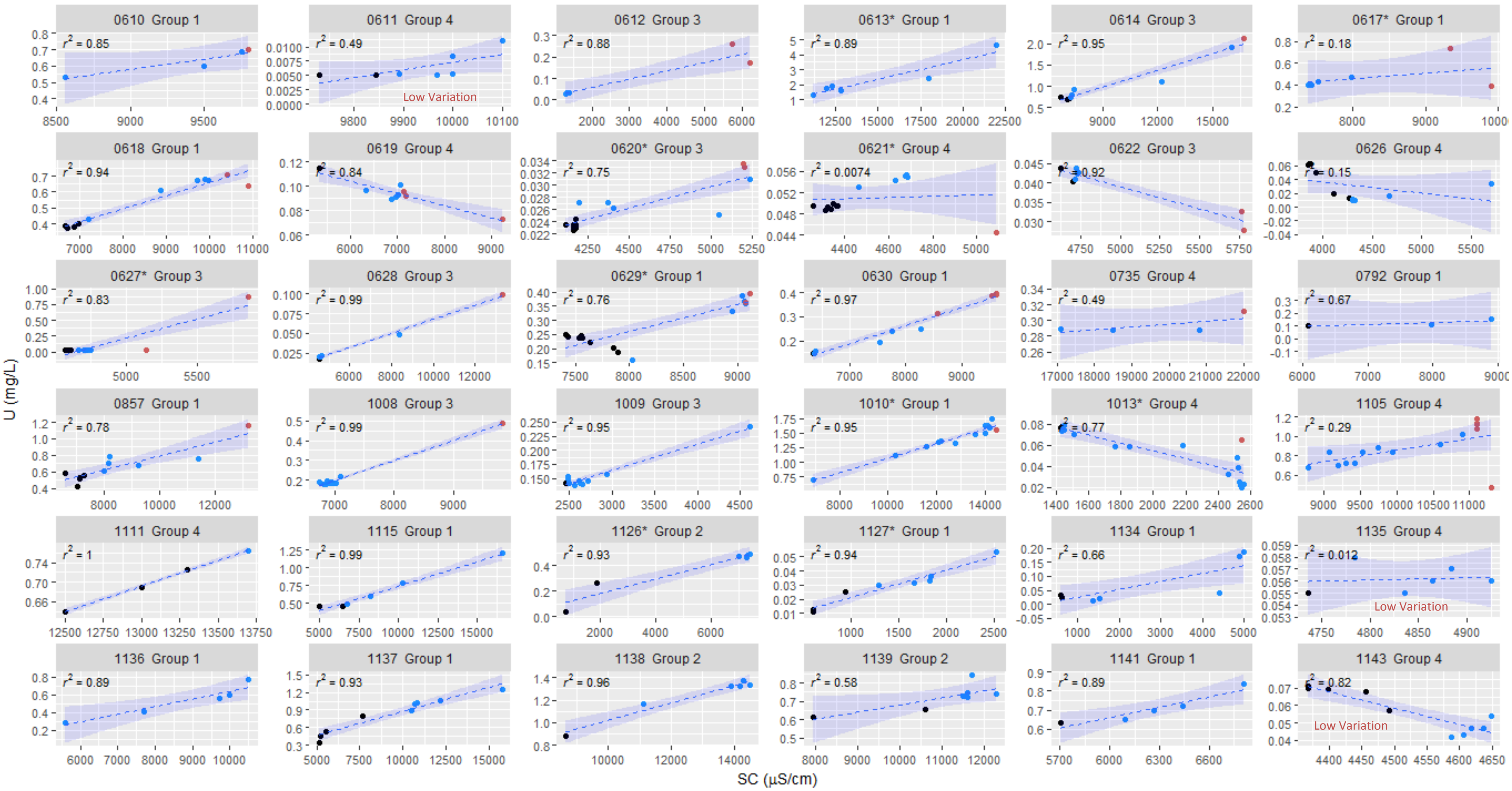
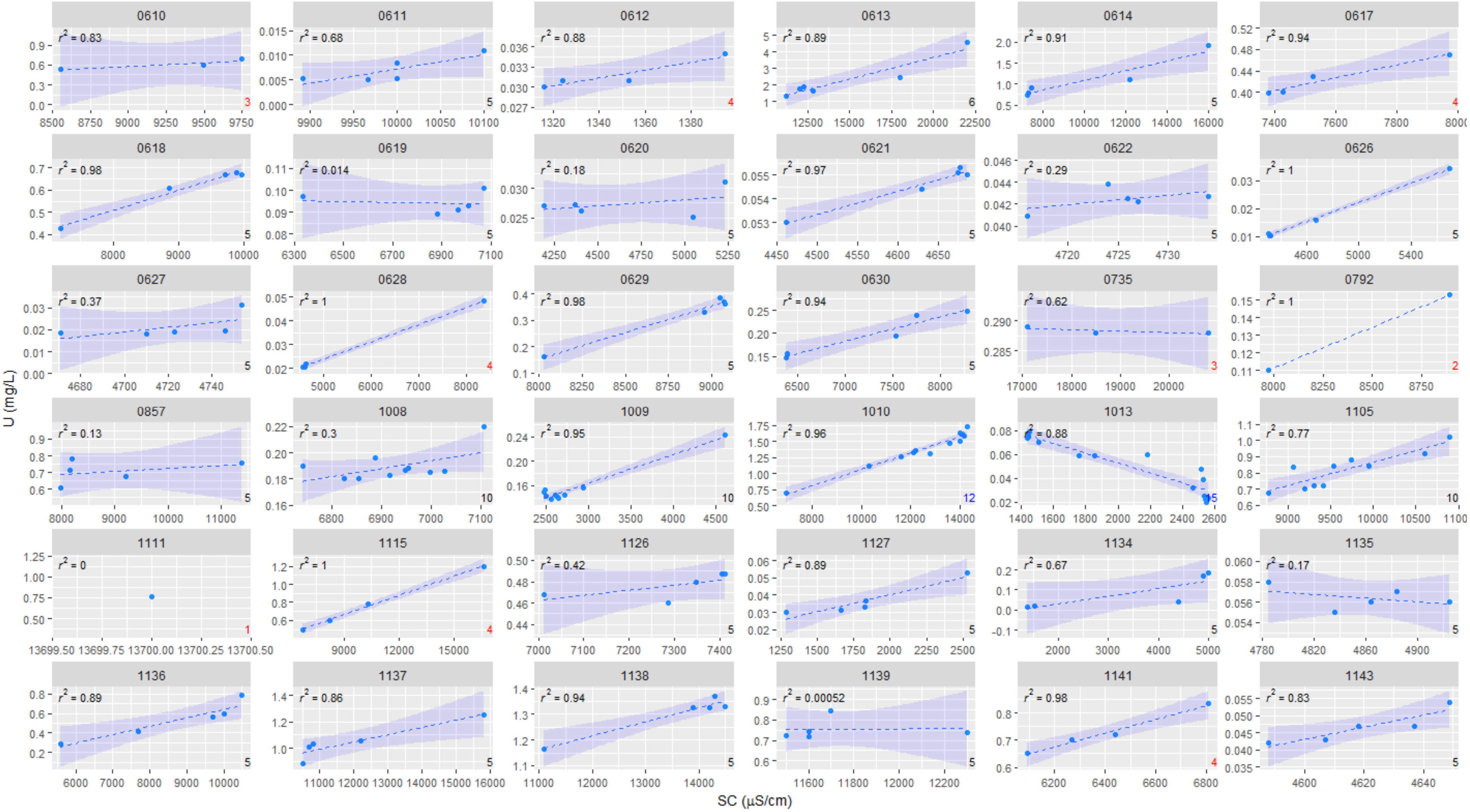
[15] As discussed in Section 2.0, the sample size corresponds roughly to the water thickness (in ft) within each well. SC measurements were taken at 0.5 ft intervals; samples for chemical analysis were collected at 1 ft intervals.



Linear regression line and corresponding 95% point-wise CI
r^2 = coefficient of determination
● Upper casing ● Screened interval ● Sump

Notes:
Well IDs are followed by the profile categories or groups defined in Table 6.
Wells having low variation in the SC profiles (CV ≤ 0.03) in both study phases are also noted.

Figure 63. SC Versus Uranium in Shiprock Site Phase II Vertical Profiles and Corresponding r^2 Values, All Well Intervals



----- Linear regression line and corresponding 95% point-wise CI
r^2 = coefficient of determination

Notes:
Corresponding number of samples (*n*) in screened interval listed in lower right hand corner of each plot. Where *n* < 5, values are listed in red.
Well IDs are followed by the profile categories or groups defined in Table 6.

Figure 64. SC Versus Uranium in Shiprock Site Phase II Vertical Profiles and Corresponding r^2 Values, Screened Interval Only

To evaluate whether there is any spatial component influencing the magnitude of correlations, Figure 65 maps the r^2 values yielded using the combined data set plotted in Figure 63. In this figure, points are color-coded based on the magnitude of the correlation coefficient (r), where blue (●) and red (●) points denote positive and negative linear associations, respectively. These distinctions are useful for identifying wells where uranium concentrations were anomalously high in the upper casing portion of the well (e.g., wells 0619, 0626, 1013, and 1143; results provided in Appendix E-2). Although there is no apparent spatial pattern in the distribution of r^2 values shown in Figure 65, overall there is a fairly strong agreement between SC and uranium in most of the Shiprock site wells profiled.

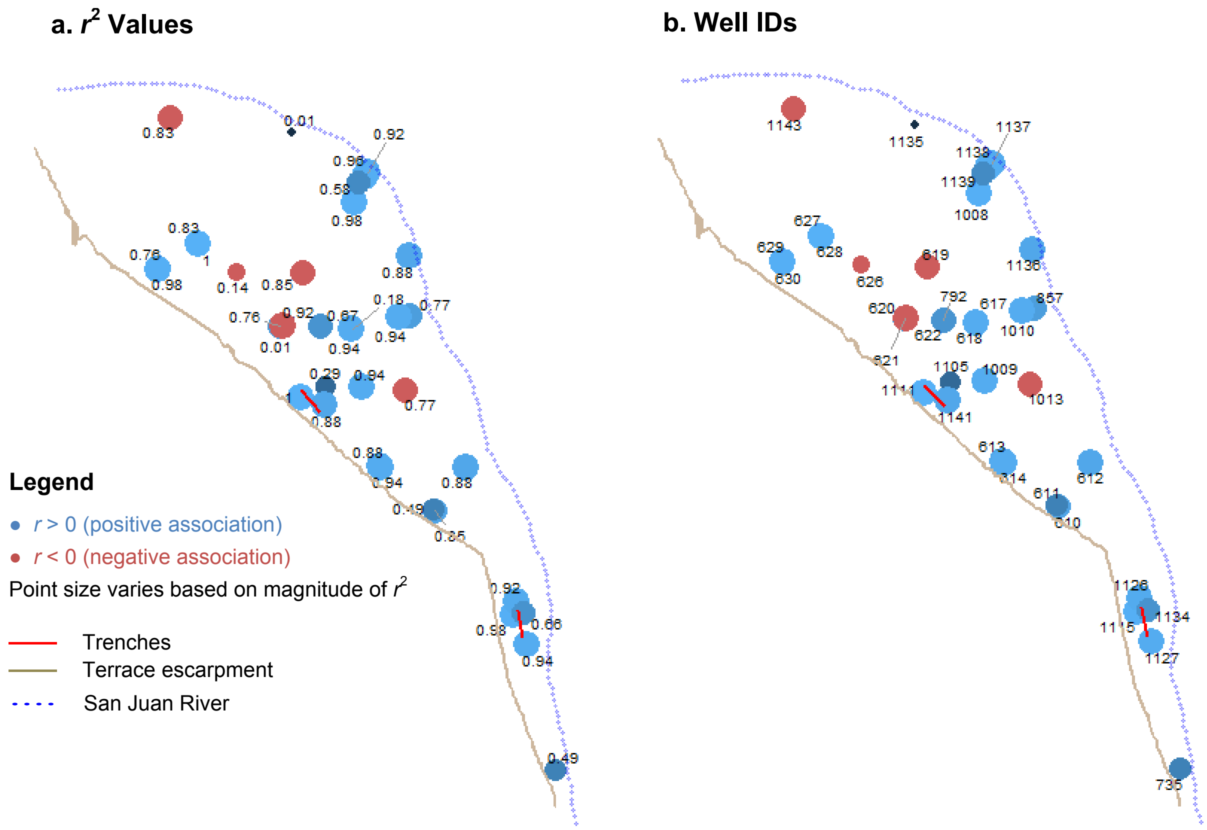
Because of the small sample sizes in the profile data set discussed above, similar plots were generated using historical SC and uranium results for the 57 wells that are routinely monitored on the Shiprock site floodplain (DOE 2018a). In general, wells with higher salinity levels and uranium concentrations have greater variation in the SC and uranium profiles. The presentation of correlation results is arranged to illustrate this.

Figure 66 plots SC versus uranium for the 34 wells with uranium consistently above the 0.044 mg/L standard. Figure 67 plots the correlations for the remaining 23 wells. In both figures, points are color-coded to reflect the relative sampling date. Darker points (●) correspond to samples or measurements taken early in the 2000–2017 period reflected, while lighter points (●) and correspond to more recent measurements. For the subset of wells with higher uranium concentrations (Figure 66), there is generally very good agreement between SC and uranium. There are exceptions (e.g., wells 0610 and 0855), but most correlations are strong (r^2 > 0.8–0.9). Correlations are somewhat weaker in the wells with lower uranium concentrations (Figure 67); this applies in particular to those wells with uranium concentrations consistently below the 0.044 mg/L standard (Figure 67b). Based on these results, combined with the correlations established based on the vertical profiles, SC could be used as a surrogate for uranium—not in all wells, but in many.

To conclude the evaluation of correlations between SC and Shiprock site contaminants (uranium and sulfate), historical data for both constituents were plotted with SC versus time. This was done only for the 26 wells that were profiled as part of this study that are routinely monitored. Using LM data from 2000–2017, Figure 68 and Figure 69 plot time trends of uranium and sulfate (concentration scale shown on left *y*-axis) along with corresponding SC measurements (concentration scale shown on right *y*-axis).

The data plotted in Figure 68 (uranium concentrations and SC over time) are the same as those in Figures 66 and 67, but in Figure 68 the date is plotted on the *x*-axis and time-trend plots for both parameters are overlain to facilitate comparison. In this figure, the well-specific data plots indicate reasonable correlation between the uranium and SC over time. There are exceptions, for example as shown for wells 0611, 0612, 0626, and 0792, but for most wells the patterns are similar. In Figure 69, the agreement between SC and sulfate is so striking that for some wells (e.g., 1135, 1137, and 1138) the sulfate result (●) is barely visible (results are overlain by the corresponding SC data [●]).

Although the plotting approach used in Figure 68 and Figure 69 (double-*y*-axis combined with semilog scale) can be misleading if not evaluated carefully, these figures demonstrate generally good agreement between historical SC measurements and uranium and sulfate concentrations.



Notes:
Because some wells are closely nested (e.g., wells 0620, 0621, and 0622), in some cases small points (those with low r^2 values) are masked by the larger points. For example, the point showing the weak correlation for well 0617 ($r^2 = 0.18$) is masked by the larger point reflecting a strong correlation for colocated well 0618 ($r^2 = 0.94$).

Values of r^2 ranged from 0.01 (wells 0621 and 1135) to 1 (Trench 1 well 1111).

When comparing r^2 values shown in Figure 63 with those plotted above, for some wells (e.g., well 1137), there are slight (±0.01) differences in r^2 values. These differences reflect the different rounding approaches applied to corresponding correlation coefficients (*r* values) used to generate the two figures.

Figure 65. Bubble Plot of r^2 Values for SC Versus Uranium, Phase II Profile Results All Measurements (corresponding data plotted in Figure 63)

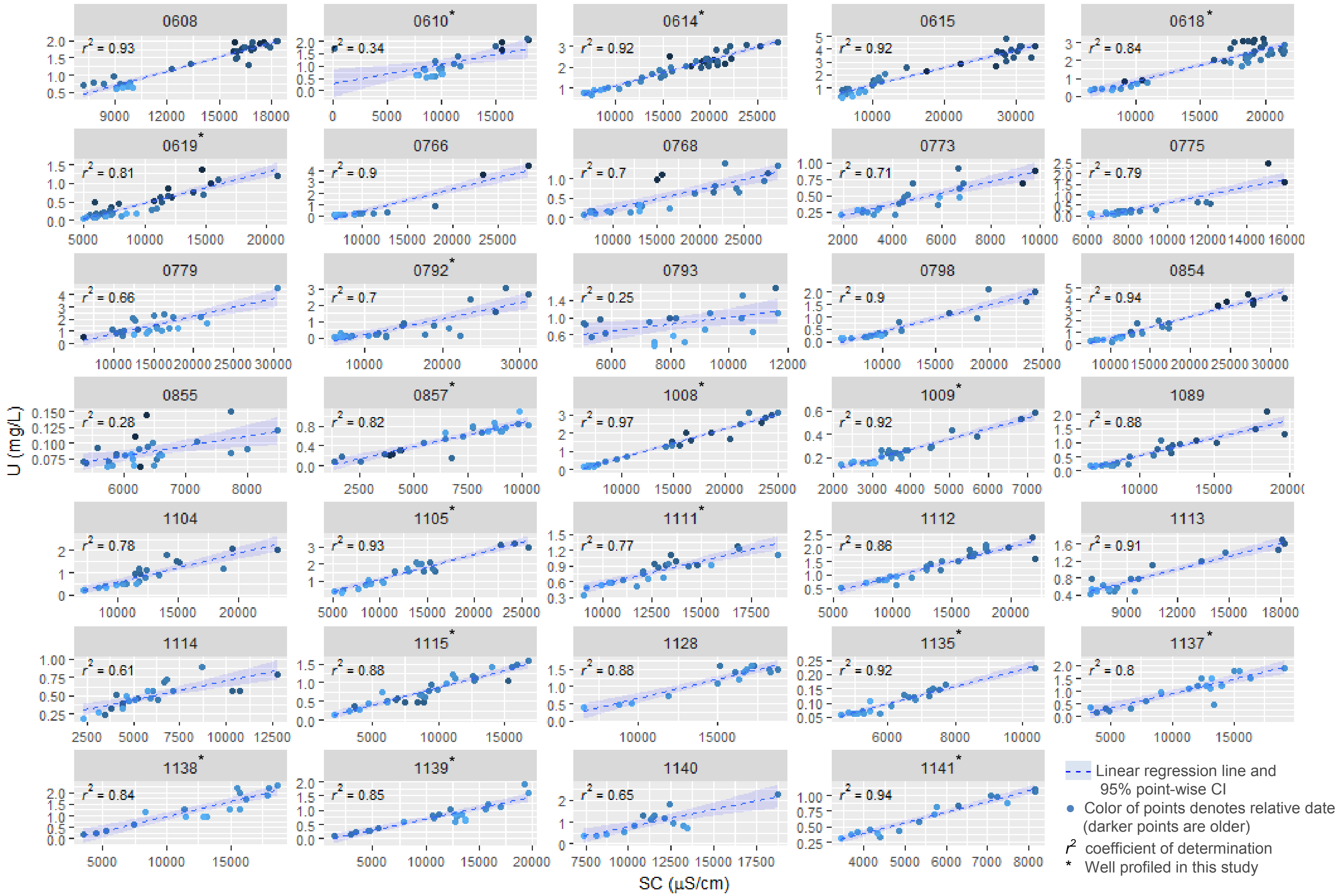


Figure 66. SC Versus Uranium in Shiprock Site Floodplain Wells Based on Routine Monitoring Results, Wells with Uranium > 0.044 mg/L 2000–2017

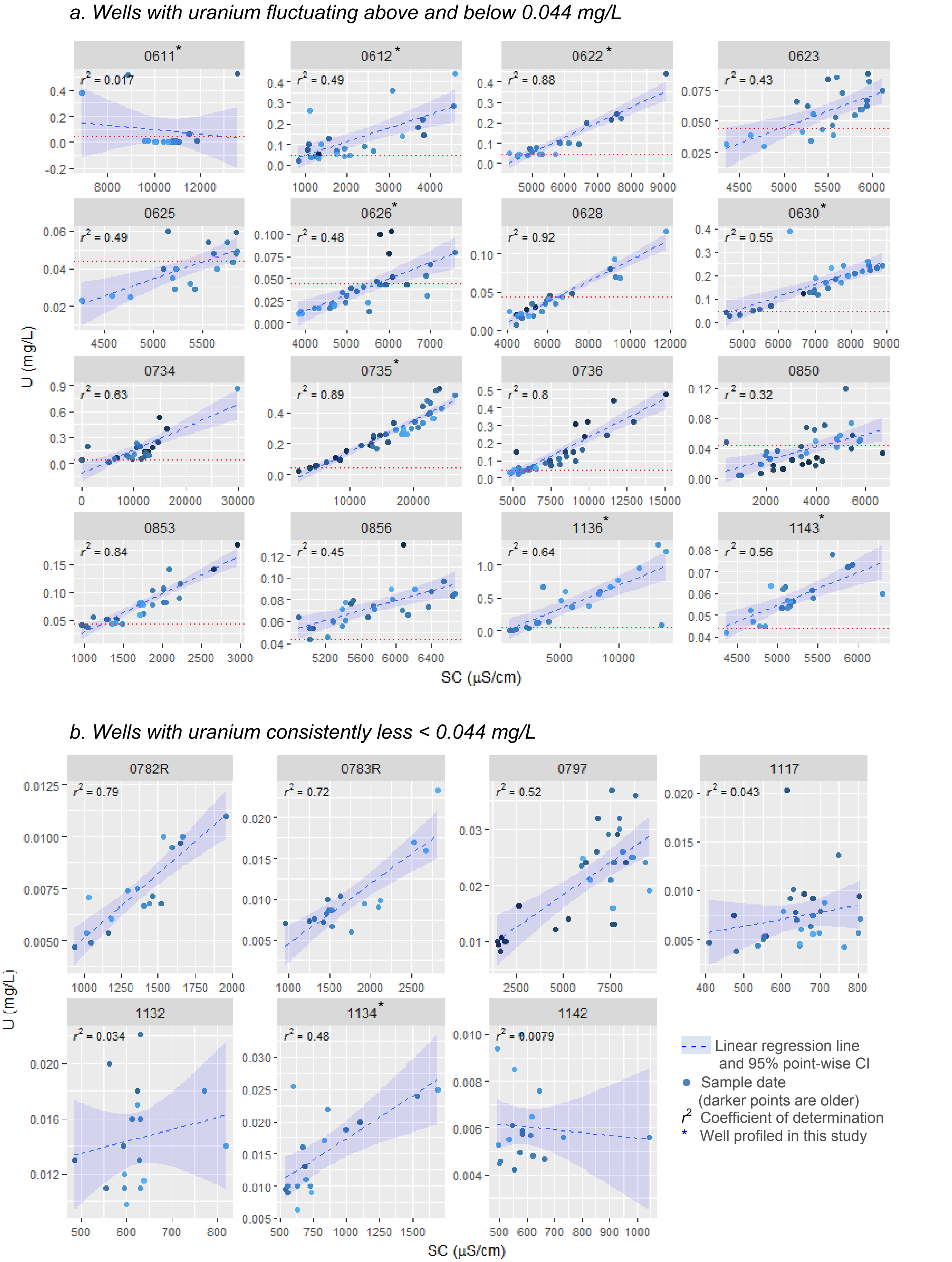


Figure 67. SC Versus Uranium for Remaining Routinely Sampled Shiprock Site Floodplain Wells 2000–2017

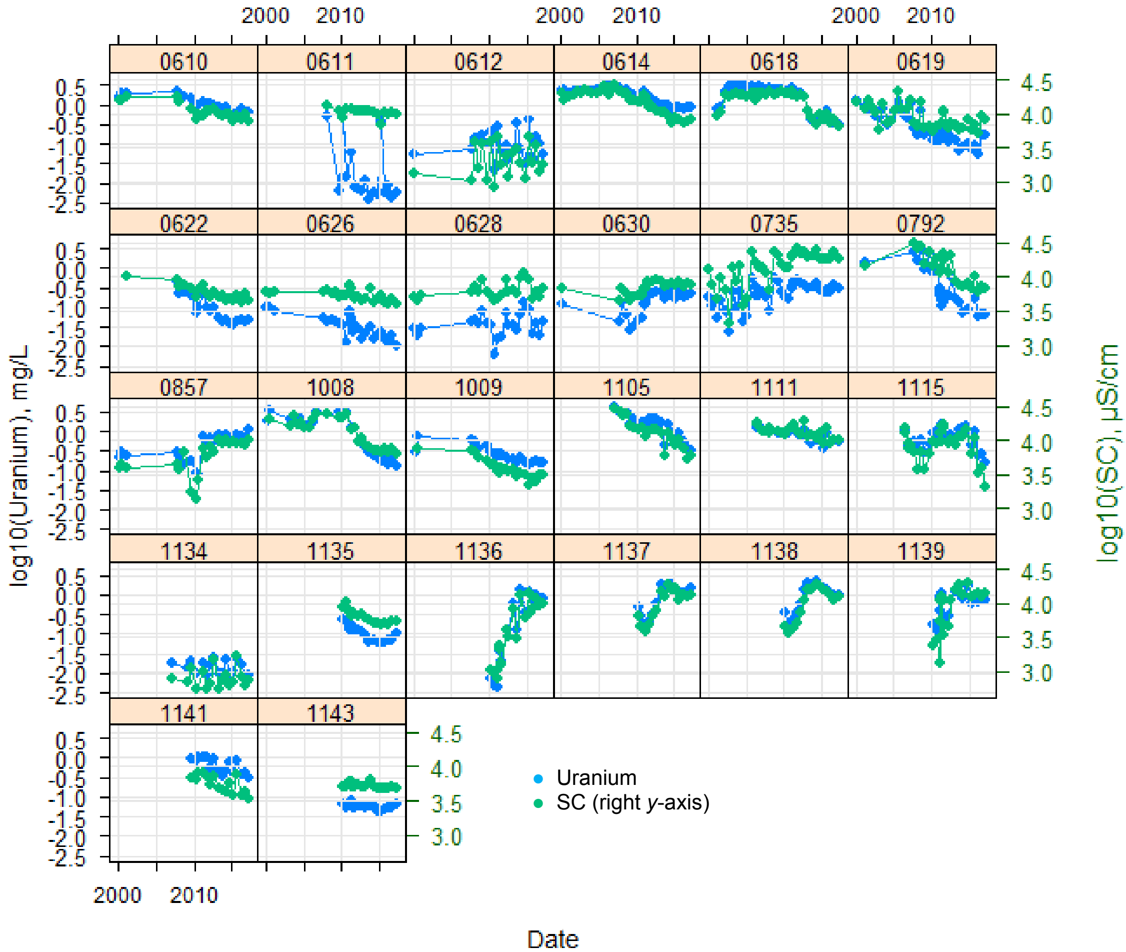


Figure 68. Time Trends of Uranium Versus SC: Routine Monitoring Results Wells Profiled in Phase II of the Variation Project Sampled Wells, 2000–2017

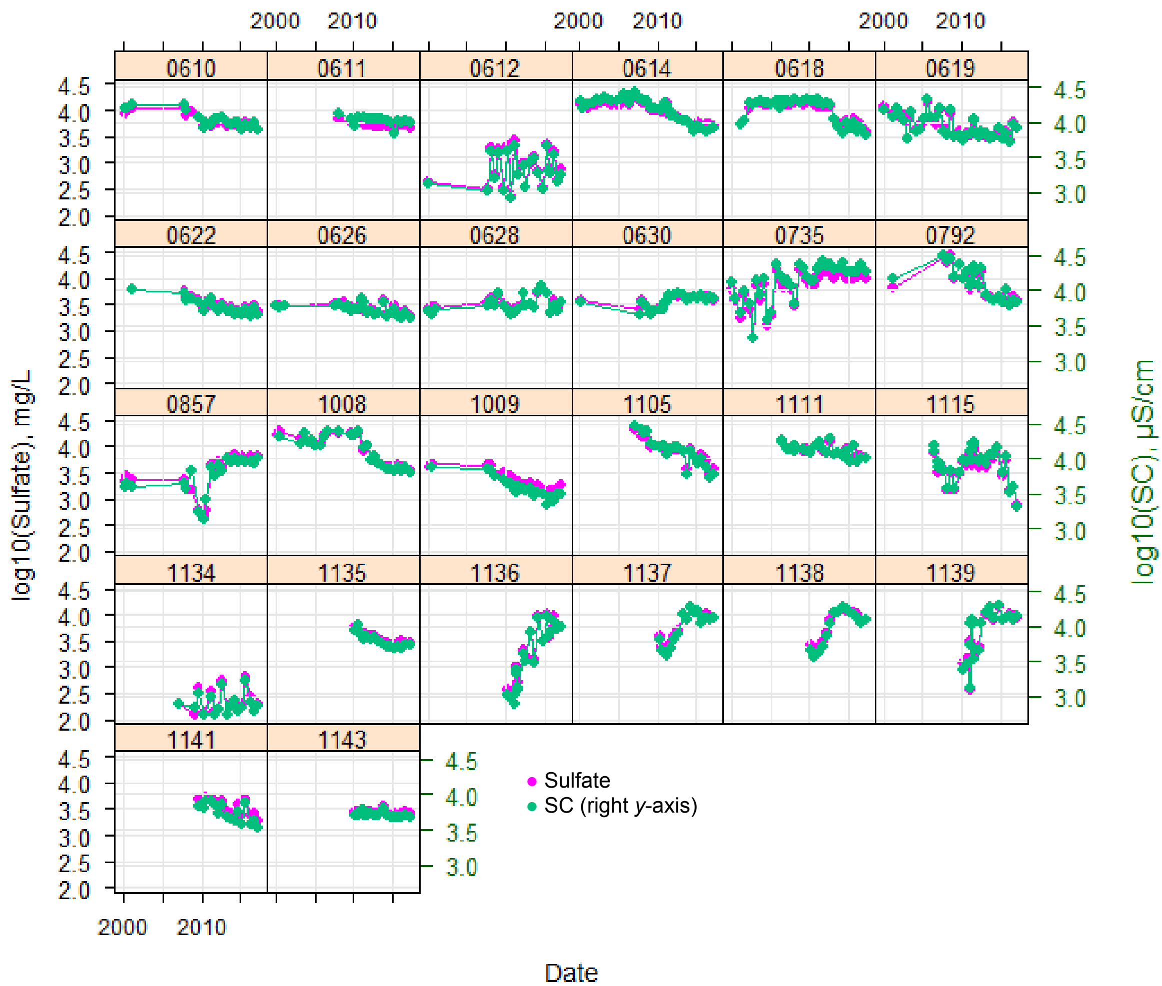


Figure 69. Time Trends of Sulfate Versus SC: Routine Monitoring Results Wells Profiled in Phase II of the Variation Project Sampled Wells, 2000–2017

5.6 Routine Monitoring Results Versus Vertical Profiles

To assess whether the vertical variation observed in Shiprock site wells might explain the historical variation in uranium concentrations, Figure 70 plots historical annual monitoring results (2000–2017) along with the 2015 profile results in a manner similar to the presentation in Figure 3. Vertical profile results are plotted vertically along the right *y*-axis. Points are color-coded to denote the corresponding portion of the well: upper casing (●); screen (●); and sump (●). The range of the profile measurements is denoted by a vertical line (|). Measurements from all intervals are shown for reasons discussed previously (discrepancies in some well logs and historic sampling of the sump region).

In most cases, the range in the profiles is consistent with recent routine sampling results. That is, the within-well variation could explain much of the historical variation observed. This is more apparent in Figure 71, which plots the same data but only for the last 5–6 years (2012–2017). This was done because significant decreases in uranium concentrations in some wells since 2000 (e.g., well 0610) mask more recent trends. The wells with the greatest degree of within-well variation in uranium concentrations, that is also consistent with corresponding historical fluctuations, include: 0612, 0626, 0628, 0857, 1136, 1137, and 1143.

It is not within the scope of this report to evaluate the degree to which vertical variation can explain apparent trends in the data. For example, at most of the wells on the floodplain, trends (increasing or decreasing) are expected due to plume migration and natural attenuation processes. Many factors, including localized effects of remediation pumping, river and groundwater level fluctuations, and transport processes could explain the temporal variation. Examples of sometimes wide (often seasonal) fluctuations in water levels are shown in Figure 72. However, the degree of vertical variation in not only SC, but concentrations of uranium and sulfate, demonstrate the importance of recording sample elevations and verifying screened interval depths.

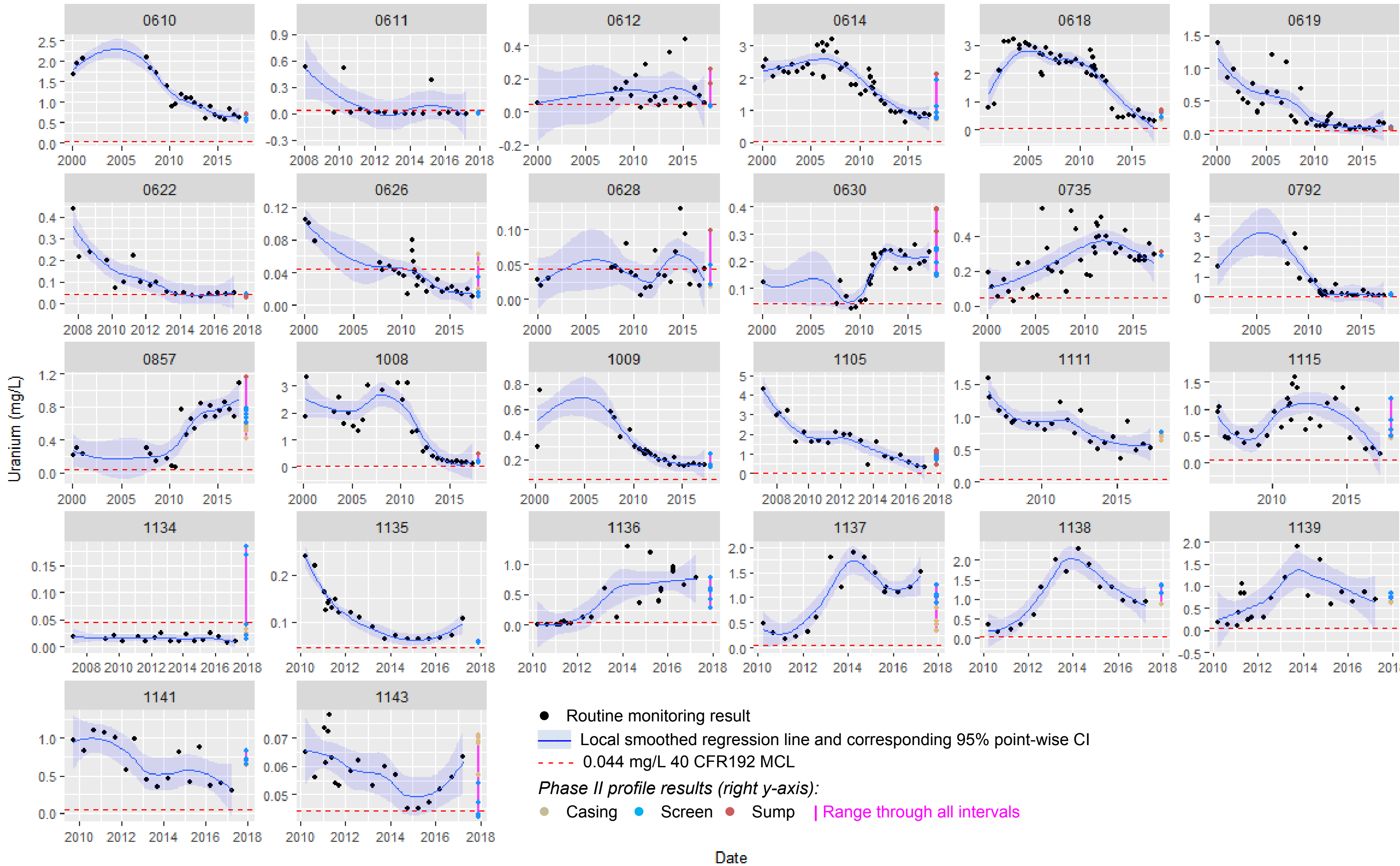
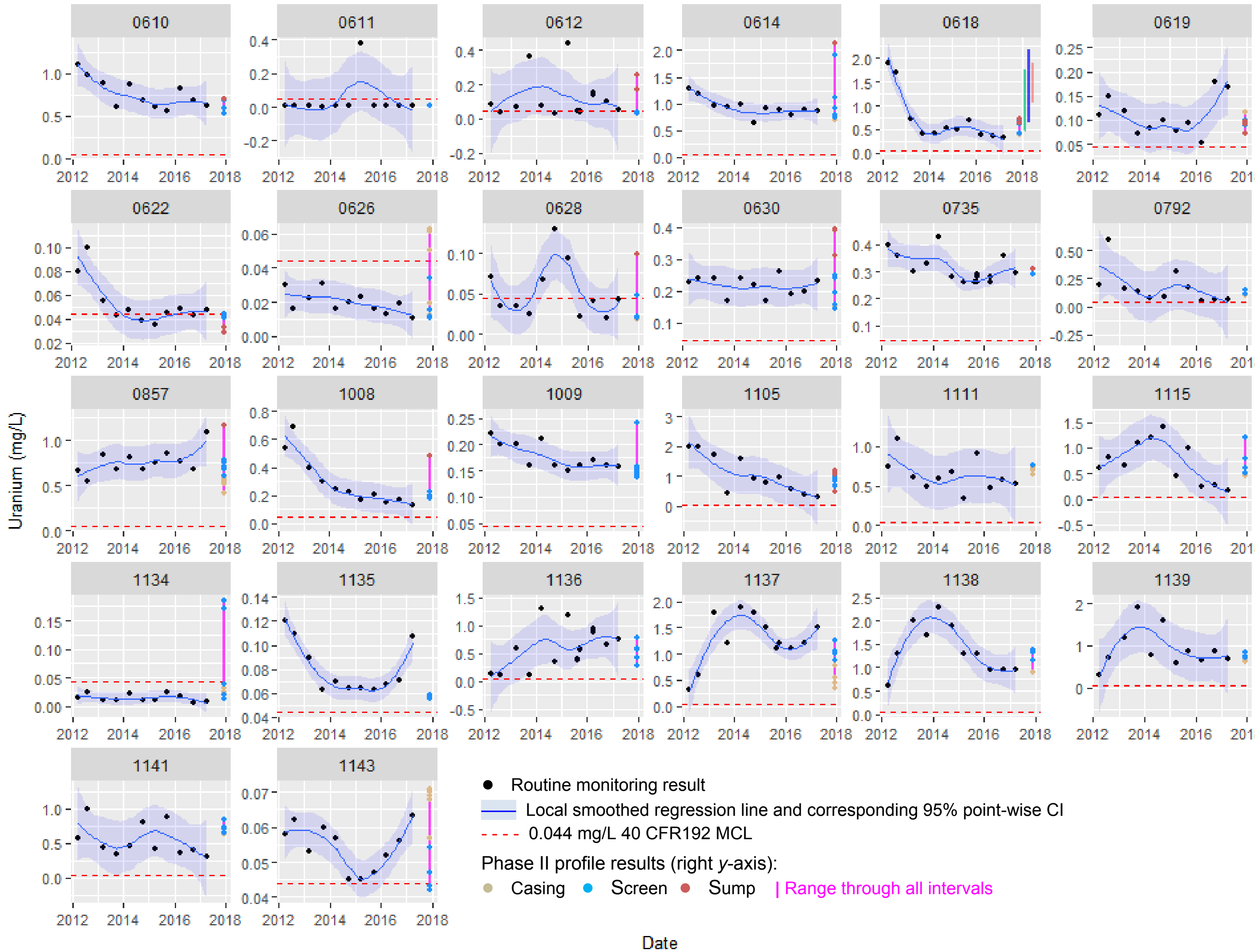


Figure 70. Historical Trends of Uranium in Shiprock Wells Profiled in Phase II, 2000–2017



Note: As discussed in Section 1.2, well 0618 was profiled several times for uranium prior to this study (between May 2012 and February 2013). The vertical lines closest to the right y-axis in the plot above correspond to the range in uranium concentrations measured during those initial profiles. As shown, there was more variation in earlier profiles than measured in 2015.

Figure 71. Historical Trends of Uranium in Shiprock Site Wells Profiled in Phase II, 2012–2017
Zoom View of Figure 70 to Facilitate Comparison of Vertical Profile Results with More Recent Trends

5.7 Comparison of Low-Flow Versus High-Flow Sampling Techniques

To provide insight into whether or not sample results differ depending on the collection method (low-flow vs. high volume purge), mid-screen samples were collected using high-volume purge methods in 6 of the 36 Shiprock site floodplain wells sampled for this study. After the SCT profile and incremental chemical sampling was performed, a minimum of 3 casing volumes of groundwater was removed. After water levels equilibrated and SCT profiles were obtained, 250 mL samples were taken at the mid-screen depth for analysis of remaining parameters. Figure 73 plots the vertical profile results using low-flow sampling methods (●) along with the corresponding mid-screen sample results following the high-volume purge (●). Apart from well 0612, in which the uranium concentration was much higher in the high-volume purge sample, results were in good agreement.

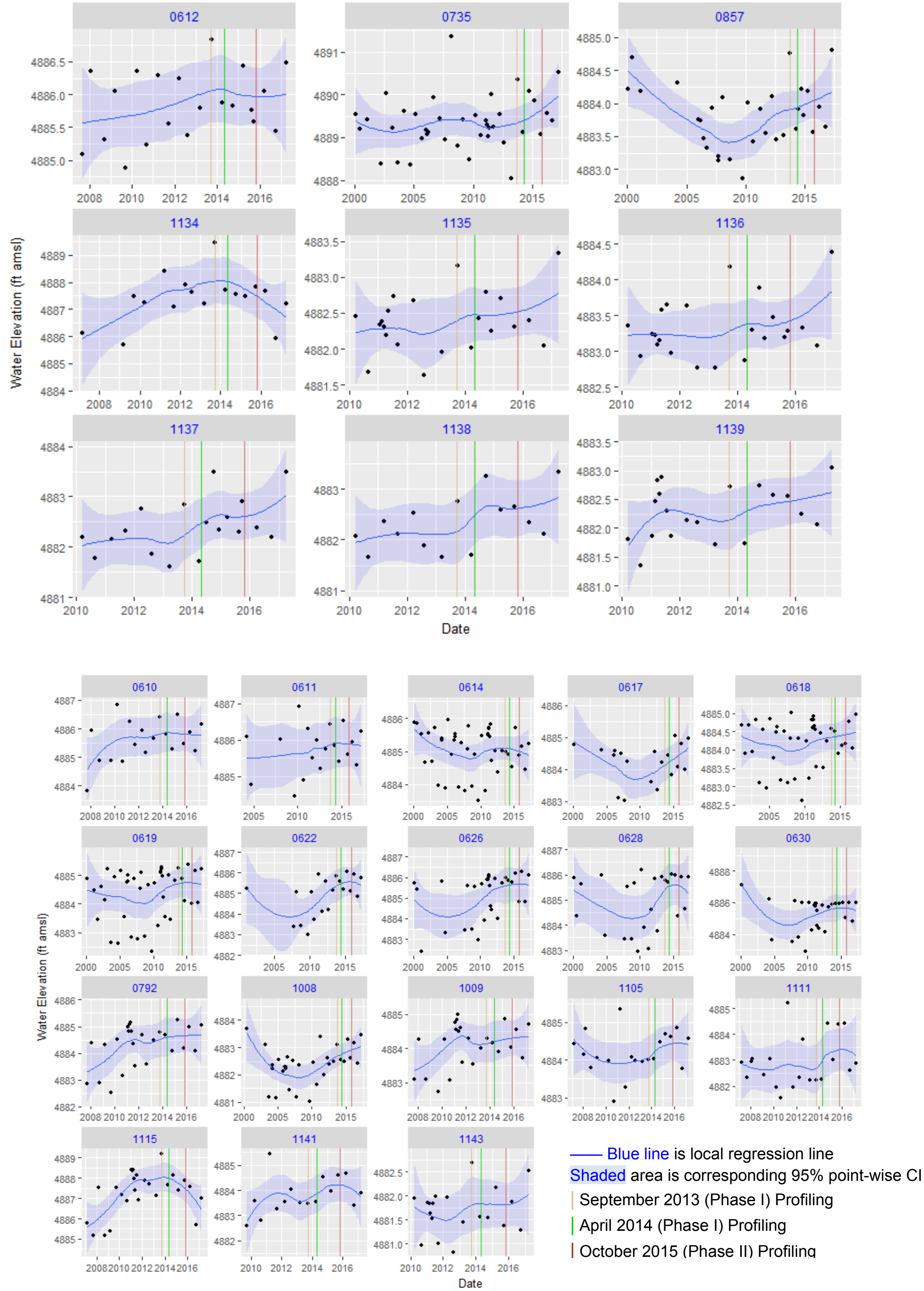
Based on this small well subset, these results indicate that the low-flow sampling approach used at the site for approximately the last 15 years yields results that are similar to those obtained using high volume purge methods, provided samples are collected at the mid-screen interval. Also, apart from well 0612, the high volume purge sample results appear to be representative of mid-screen aquifer conditions. Nonetheless, as discussed above, the magnitude of variation found in Shiprock site floodplain wells warrants sampling at consistent depths. If mid-screen depths are determined based on the well logs, then it is important to verify that information. Downhole video profiles conducted for this study identified discrepancies exceeding 1 ft in seven wells (details provided in Appendix B, Table B.2.3):

- Wells 0610, 0611, 0613, 0626, 1111, 1141—downhole videos indicate that screens are at least 1 ft higher (more shallow) than the depths indicated in the well construction logs
- Wells 0629, 0630 (note Figure 54 and corresponding anomalous ^{222}Rn profile), and 0735—downhole videos indicate that screens are at least 1 ft lower (deeper) than the depths indicated in the well construction logs.

5.8 Shiprock Site Floodplain Summary of Findings

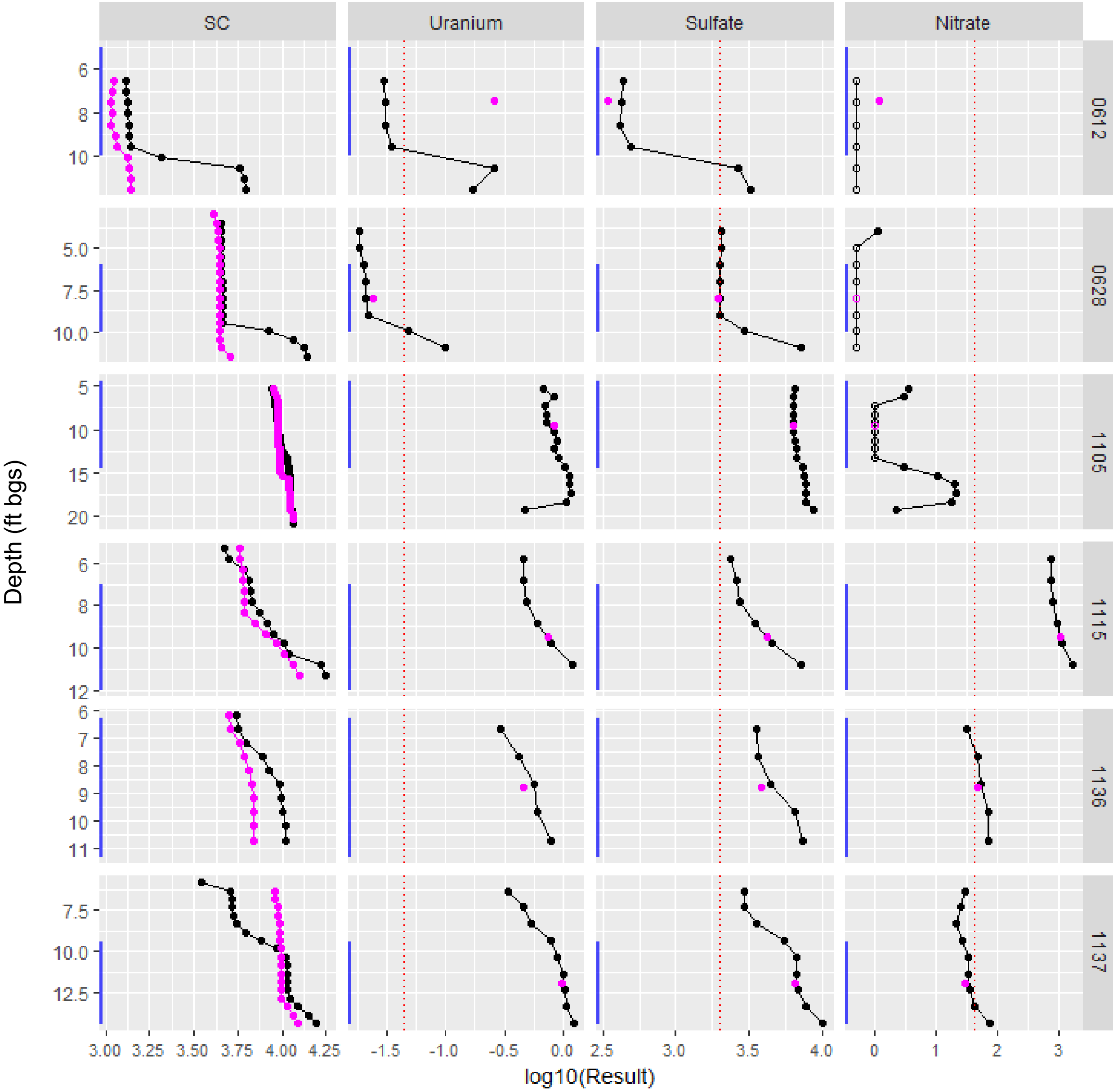
Unlike the Durango processing site, where significant vertical variation in uranium concentrations was limited to a few select wells, at the Shiprock site, vertical within-well variation of uranium was the norm rather than the exception. The prevalent and large variation in SC was confirmed for uranium, sulfate, and other major ion concentrations. In many of the wells profiled, in particular those with the highest degrees of variation in Phase I, there is a strong linear relationship between SC and uranium, as well as other analytes. These findings support using SC as a cost-effective surrogate for monitoring uranium and sulfate in wells where this correlation has been established. Comparison of SC with uranium concentrations based on routine monitoring results confirmed this conclusion. Given inter-well differences in location, well configuration, and contaminant magnitude, the correlation between SC and uranium should be established on a well-specific (vs. aggregate sitewide) basis.

Vertical profiles of ^{222}Rn in monitoring wells are useful in discerning zones with high groundwater influx and zones that are relatively stagnant. As such, ^{222}Rn profiles could help optimize monitoring well screen placement or in situ groundwater treatment strategies.



Hydrographs for the following wells profiled in Phase II of this study are not shown because water levels are not routinely monitored: wells 0613, 0620, 0621, 0627, 0629, 1010, 1013, 1126, and 1127.

Figure 72. Hydrographs for Shiprock Site Floodplain Wells Profiled in Phase II: 2000–2017



Notes:

| Screened interval

● Vertical profile results using low-flow sampling methods

● SC measurement or mid-screen sample result after high-volume purging of well

○ BDL result

Vertical dotted line (····) denotes corresponding 40 CFR 192 MCL or background level:

0.044 mg/L uranium; 2000 mg/L sulfate (background); and 44 mg/L nitrate as NO_3

Figure 73. Phase II Profiles vs. High-Flow Mid-Screen Result for Shiprock Well Subset

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6.0 Discussion

The findings documented in Sections 4 and 5 for the Durango and Shiprock sites confirm that SC and concentrations of selected major ions have large vertical variation, typically increasing with depth, in most wells profiled. Uranium, the primary milling-related constituent monitored at LM UMTRCA sites, also varies with depth in most wells.

6.1 Variation in Well Chemistry

The magnitude of vertical chemical variation was different at each site profiled and, in the case of uranium, the slope of the profiles was different at each site as well (increasing or decreasing with depth). At the Durango processing site, the most notable variation was measured in wells screened in different strata. For example, groundwater chemistry was very different in portions of the wells screened in the alluvium versus the Mancos Shale. In several of these wells within the mill tailings area, uranium concentrations varied by 1 to 2 orders of magnitude within the screened interval, encompassing values both above and below the 0.044 mg/L standard. These results suggest that screening wells in several formations introduces uncertainty into the sampling regime and data interpretations, especially if the intent is to monitor groundwater conditions in the alluvium.

At the Durango processing site raffinate ponds area, the most notable variation in uranium chemistry was measured in wells 0598 and 0884, both of which are routinely monitored and screened in the Menefee Formation. Well 0598 is also screened in the Point Lookout Sandstone, which is separated from the overlying Menefee Formation by the Bodo Fault zone. The range in uranium concentrations measured within the screened interval in both of these wells was of sufficient magnitude to impact trend analyses and attenuation rate estimates if sample depths have not been consistent.

Unlike the Durango processing site, where significant vertical variation in uranium concentrations was limited to a few select wells, at the Shiprock site vertical within-well variation of uranium (along with other constituents) was the norm. The prevalence of highly variable SC profiles in wells installed on the floodplain was confirmed to also be true for uranium, sulfate, and other major ions. The higher prevalence of chemically stratified wells at the Shiprock site (vs. at the Durango site) might be due to differences in geology and associated hydrogeological properties between the two sites. For example, many of the Durango processing site wells are deeper, whereas those at the Shiprock site floodplain are primarily screened in alluvium and have water levels well above the Mancos Shale. Additionally, salinity in most of the Shiprock site wells is higher than that in the Durango processing site wells.

The wells and analytes discussed in this report represent only a small subset of the data collected for the Phase II profiling effort. Although beyond the scope of this evaluation, more detailed examination of the analyte and well-specific profiles provided in Appendixes C through E might reveal useful information regarding chemical signatures that could further enhance understanding of contaminant behavior at these sites.

6.2 Correlations Between SC and Primary Site Constituents

A goal of this study was to determine whether there is a correlation between SC and site contaminant concentrations and, if so, to assess whether SC could be used as a viable surrogate that could be measured in lieu of more costly sampling and analysis of chemical concentrations.

In general, no strong correlation was found between uranium concentrations and SC in Durango processing site wells. Although concentrations of dissolved ions and uranium did vary in many of the wells profiled, no consistent pattern was observed. In contrast to the trends found for SC (increasing with depth), in most mill tailings area wells, uranium concentrations decreased with depth. As such, the use of SC as a surrogate or indicator of uranium concentrations at this site is not recommended.

This was not the case at the Shiprock site. In many of the wells profiled, in particular those with the highest degrees of variation measured in Phase I, there is a strong linear relationship between SC and uranium, as well as other analytes. These findings support using SC, an easily obtained measure of salinity, as a cost-effective surrogate for monitoring uranium and sulfate, the primary milling-related constituents monitored at the site. Implementation of such an approach is recommended on a case-by-case basis for the subset of wells in which a strong correlation was established. There were exceptions, particularly in wells with less variation or some wells influenced by river flows or remediation pumping. However, a strong correlation between SC and uranium was found in most of the 36 Shiprock wells profiled ($r^2 \geq 0.75$ in 26 wells, 14 of which had $r^2 > 0.90$). Comparison of historical SC measurements with corresponding uranium concentrations based on routine monitoring results confirmed this conclusion.

Using SOARS instrumentation, SC can be continuously measured using downhole sensors. Because no pumping is required to obtain measurements, this method has minimal disruption to the water column and provides a semicontinuous set of concentration data that can be used to provide insight into transient behavior of site contaminants in groundwater. The simplicity of the method allows a large quantity of data to be collected at relatively low cost. The current sampling program at the Shiprock site is one of the most extensive and costly of the UMTRCA sites currently managed by LM (DOE 2013). On the floodplain alone, about 60 monitoring wells are sampled twice a year. A mandate under Goal 1 of LM's *2016–2025 Strategic Plan* (DOE 2016a) is to understand and improve the long-term sustainability of environmental remedies in a cost-effective manner. The use of SC as a surrogate for uranium would not only support that objective but continued monitoring might also improve LM's understanding of contaminant migration in groundwater.

6.3 Potential Sources of Variation

Results of this study confirmed initial hypotheses that wells with highly variable SC profiles are also characterized by highly variable major ion and, in many cases (particularly at the Shiprock site), uranium profiles. It is beyond the scope of this report to evaluate the underlying geochemistry of each of the 921 analyte profiles obtained or the factors possibly contributing to the vertical variation measured in the profiles.

When this study plan was developed, it was anticipated that the following factors could account for the observed variation:

- Natural factors such as density-dependent flow or aquifer heterogeneity
- Anthropogenic factors, such as sampling technique (low-flow versus standard or high-volume purge)
- Pumping or borehole effects (e.g., casing degradation)
- Well construction and configuration (depths, screen placement and length, saturated thickness)
- Aquifer lithology
- Proximity to pumped wells or surface water bodies, water elevations (temporal issues)

Ultimately it was not possible to explain how (if at all) these factors account for the measured variation. However, some preliminary hypotheses as to the cause of the high variation can be made based on the data presented in this report.

The ^{222}Rn profiles presented in Figure 17 and Figure 58 generally indicate higher ^{222}Rn levels in alluvial wells immediately above the alluvium/bedrock contact in wells at the Durango processing site mill tailings area and Shiprock site, respectively. Radon-222 profiles from the Durango processing site raffinate ponds area (Figure 32) were obtained from below the alluvium/bedrock contact and are excluded from this discussion. The increasing radon concentrations indicate higher groundwater flux rates near the alluvium/bedrock contact. This could be attributed to coarser alluvial sediments at the base of the alluvial aquifer (i.e., it reflects a fining-upwards sedimentary sequence) and corresponding higher hydraulic conductivities in that region. This would typically result in preferential flow of groundwater and constituents at the base of the alluvial aquifer. This hypothesis is supported by the SC profiles presented in Figure 11 and Figure 45. As discussed in previous sections, high SC typically correlates with high sulfate concentrations associated with mill-related contamination. Many SC profiles show increasing SC (and sulfate) concentrations at the base of the alluvial aquifers, which also support the hypothesis of preferential groundwater flow.

Another process that may contribute to variation in the profiles is density effects. SC is reflective of salinity levels (dissolved ions) in groundwater. High salinity levels increase the density of groundwater. Therefore, the most saline (and contaminated) water is expected to sink toward the bottom of the aquifer. Some Durango processing site SC profiles in wells that are screened across the alluvium–Mancos Shale contact suggest that high density groundwater is settling in the portions of the well screened in the Mancos Shale. Monitoring wells 0630, 0631, 0622, 0857, and 0859 display low or increasing SC levels with depth in the alluvium and stable, high SC levels within the Mancos Shale portion of the well. The hydraulic conductivity and low groundwater flux in the Mancos Shale (stagnation zone) may allow the denser, high salinity groundwater to settle to the bottom of these wells. Density-driven flow may be more significant at higher salinities.

The groundwater density effects may be similar to those described in seawater intrusion studies. Polemio et al. (2009) and Levanon et al. (2013) both showed that SCT profiling was an effective tool for defining patterns of seawater intrusion.

6.4 Implications to Interpretation of Routine Monitoring Results

For most Durango processing site wells, temporal trends of uranium based on routine monitoring results appear to be unrelated to corresponding ranges measured in the vertical profiles. Based on this observation, samples collected during routine monitoring events have probably been collected at consistent depths historically. For most of the Shiprock site floodplain wells profiled, the range in the vertical uranium concentration profiles is consistent with recent routine sampling results. There are some wells (e.g., 0857, 1136, and 1137), however, where the within-well variation could explain historical trends. In two of these near-river wells (0857 and 1137), contaminant concentrations have been increasing in the last several years (DOE 2018a). It is important to acknowledge that increasing (or decreasing) trends are expected due to migration and attenuation of contaminant plumes. Nonetheless, results of this investigation might inform future studies regarding potential causes for these increases. Theoretically, if samples in shallow alluvial wells are not collected at consistent depths, then the vertical variation in constituent magnitudes (if measured) could account for some, if not all, of the temporal variation in these wells.

The results of this study highlight the importance of recording sample depths, especially when using low-flow sampling methods. Since this study was initiated in 2013, LM has modified its sampling protocols to require fixed sample intake depths and routine documentation of corresponding elevations. Furthermore, in evaluating contaminant masses at some LM sites, rather than assuming a uniform (single) concentration, accounting for potential subsurface variation could improve future assessments of contaminant mass and site remediation progress.

6.5 Radon-222 Profile Results

Another outcome of this study is that vertical profiles of ^{222}Rn in monitoring wells are useful in discerning zones with high groundwater influx and zones that are relatively stagnant. This information could help optimize screen placement in monitoring wells or injection wells for in situ remedies. Radon-222 concentrations were determined for 21 of the 60 wells profiled during the Phase II field investigation. These concentrations varied with depth in most of the wells profiled, ranging up to about 770 and 300 pCi/L at the Durango and Shiprock sites, respectively. These profiles indicate that portions of wells have high groundwater influx (e.g., those with ^{222}Rn > 200 pCi/L) and other portions (e.g., sumps) are more stagnant (^{222}Rn < 50 pCi/L). In many cases, the ^{222}Rn profiles indicated that most of the flow occurred in the screened portion of the well, as expected. However, some wells had low ^{222}Rn concentrations throughout the profile (in particular, some wells at the Durango site), indicating minimal groundwater influx. In Shiprock site well 0630, ^{222}Rn results were useful in identifying discrepancies in screen placement relative to data recorded in the well construction log (as indicated by the downhole video profile). Use of this technique in future studies within the LM program could improve sampling approaches, help identify monitoring well-screen degradation and potential well redevelopment needs, and better understand variations in historical water quality.

6.6 Uncertainties and Necessary Caveats

Some factors potentially affecting the results of this study warrant acknowledgement. This study focused on quantifying the degree to which SC, uranium, and other constituents or analytes varied within a well. For those wells and variables (mostly SC) where repeated measurements were conducted, in most, but not all cases, the results agreed. At both the Durango and Shiprock sites, there were a few wells where results of the initial SC profiles differed markedly from later (e.g., Phase II) profiles. These differences could be explained by different groundwater flow or water level conditions, but they could also reflect an anthropogenic source (e.g., an artifact of sampling or measurement error). For all chemical profiles, low-flow sampling methods were used and care was taken to avoid disruption to the standing water column in the well. Despite these precautions, mixing could have impacted the analytical results, particularly in low-producing wells where significant drawdown was observed. In these cases, correlations between SC and chemical concentrations would likely be affected. For example, a sample collected at a 10 ft depth after low-flow pumping might not be representative of the water chemistry at that same depth prior to sampling (when SC was measured).

Despite these caveats, results of this study demonstrate that, in most of the wells profiled, there is major variation in water chemistry with depth. Whether or not that variation corresponds to similar variation in the surrounding formation or aquifer is not known at this time.

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7.0 Summary and Conclusions

This study focused on evaluating vertical variation in concentrations of dissolved constituents in groundwater monitoring wells. In some cases, the range in specific conductance, uranium, and other constituents measured over a decade or more in a well could be reproduced in several hours by sampling the well at different depths. Based on these observations, LM undertook an investigation to determine the extent of dissolved ion and chemical variation that occurs in monitoring wells at sites managed under the UMTRCA program. Phase I of this study, conducted in 2013–2014, assessed the overall prevalence of vertical stratification in LM site monitoring wells based on measurements of SC alone. Phase II, conducted in 2015–2016 and the focus of this report, investigated whether the measured vertical variation in SC applies to site constituents, in particular, uranium. A related objective was to determine the extent to which SC correlated with uranium (or other parameters) and the feasibility of using SC as a surrogate for monitoring uranium in wells where this correlation has been established.

One of the major findings of Phase II of this study was that the analytical results for a given well, particularly at floodplain sites, can vary significantly depending on the depth at which samples are collected, even within the screened interval of the well. On the basis of the Phase II field results, this was found for uranium, sulfate, and other constituents at both the Durango and Shiprock sites. This finding is important for several reasons.

The first goal of this study was to determine the degree of correlation between SC and LM site contaminants, if any. Based on chemical profiling at the Durango processing site, there is no apparent correlation between SC and uranium, the primary indicator of milling-related contamination. As indicated above, although concentrations of dissolved ions and uranium did vary in many of the wells profiled, no consistent pattern was observed. In fact, in many of the Durango processing site wells, uranium decreased with depth, in contrast to the increasing trend observed for SC. Overall, chemical profiles in both former mill tailings area and raffinate ponds area wells were irregular and varied from well to well. This might be due to the complex geology at the site, which is underlain by five distinct geological formations. Many of the wells profiled were screened in two strata.

In about 70% of the wells profiled at the Shiprock site, in particular those with the highest degrees of variation in Phase I, there is a strong linear relationship between SC and uranium, as well as other constituents. These findings were corroborated by routine monitoring results, where correlations of paired historical SC and uranium measurements were similarly strong. With regard to the second goal of this study, in the cases where a strong correlation has been established, the Phase II data support using SC as a cost-effective surrogate for monitoring uranium and sulfate, the most routinely monitored milling-related constituents at most LM UMTRCA sites.

The third question driving this investigation was to assess whether the observed intrawell variation could improve LM's groundwater monitoring strategies at selected sites. The results of this study highlight the importance of:

(1) sampling groundwater monitoring wells at consistent depths, a prerequisite for valid trend analysis of the data, especially if chemical stratification has been measured (as feasible, accounting for seasonal water level fluctuations);

(2) recording sample depths routinely (where the "*z*" elevation component is equally important as the "*x*" and "*y*" spatial variables); and

(3) periodically verifying that those depths correspond to the representative portion of the aquifer being monitored.

LM follows well-established protocols for groundwater sampling and laboratory analysis, in accordance with established and accepted industry guidelines. In following these protocols, there was an inherent assumption that the water quality within the well screen was homogenous and representative of aquifer conditions. As a result, sample depths were not recorded routinely, and they may not have been consistent. At some LM site alluvial wells, depending on the groundwater elevation, it is likely that samples were often collected from the lower screen or even the sump portion of a well.

If, as was found in this study, dissolved ion and contaminant concentrations vary with depth in some LM site monitoring wells, this could affect interpretations of temporal trends, especially when using low-flow sampling techniques. The findings of this study underscore the importance of maintaining consistent depths when sampling and routinely documenting those depths. Since this study was initiated in 2013, LM has modified its sampling protocols accordingly, requiring fixed sample intake depths and routine documentation of those elevations.

Results of this study also highlight the importance of considering well construction (screen placement) and understanding groundwater flux patterns when developing or refining monitoring strategies. For example, at the Durango processing site, the observed variation in both SC and uranium profiles is likely attributed to the fact that many wells are screened in two formations, a factor that can introduce uncertainty into the sampling results and data interpretations.

Other conditions potentially accounting for the variation found in SC and chemical profiles in the wells profiled in this study include density-driven flow (which could account for salinity increasing with depth), preferential flow paths (including fracture flow); and stagnant zones in wells, as indicated in several ^{222}Rn profiles. Although the extent to which these factors account for the observed vertical variation is beyond the scope of this study, awareness of these potential mechanisms is important when evaluating groundwater behavior at LM sites.

A final outcome of this study is that vertical profiles of ^{222}Rn in monitoring wells are useful in discerning zones with high groundwater influx and zones that are relatively stagnant and, as such, could help optimize sampling protocols and implementation of in situ remedies. The latter, coupled with periodic downhole video profiling (to confirm screen placement and assess well integrity), could help refine groundwater sampling regimes at existing or newly transitioned LM sites.

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Appendix A

Variation Project Phase I Graphical Summary

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Preface

The Phase I report (DOE 2015) presented a brief summary of all site results and focused on the most interesting specific conductance (SC) profiles. Appendix A of the Phase I report provided corresponding statistical summaries for each site profiled. This appendix provides a graphical summary of the Phase I SC profile results in a way that is distinct from the presentation in the Phase I report. For most sites, vertical SC measurements are shown for all wells profiled. For sites where many wells were profiled (e.g., the Monument Valley, Arizona, Processing Site), the graphical summary is limited to only those wells for that are regularly sampled. In some cases, plots are annotated to facilitate identification of the wells with the most variable SC profiles.

When interpreting the following figures, it is important to acknowledge the range in values because scales are unique for each well-specific SC profile. Sample location maps, indices of variation (CVs), and additional pertinent information (e.g., the relevant historical and hydrogeological context) are provided in the Phase I report (DOE 2015). Abbreviations used throughout this appendix are defined below.

Abbreviations:

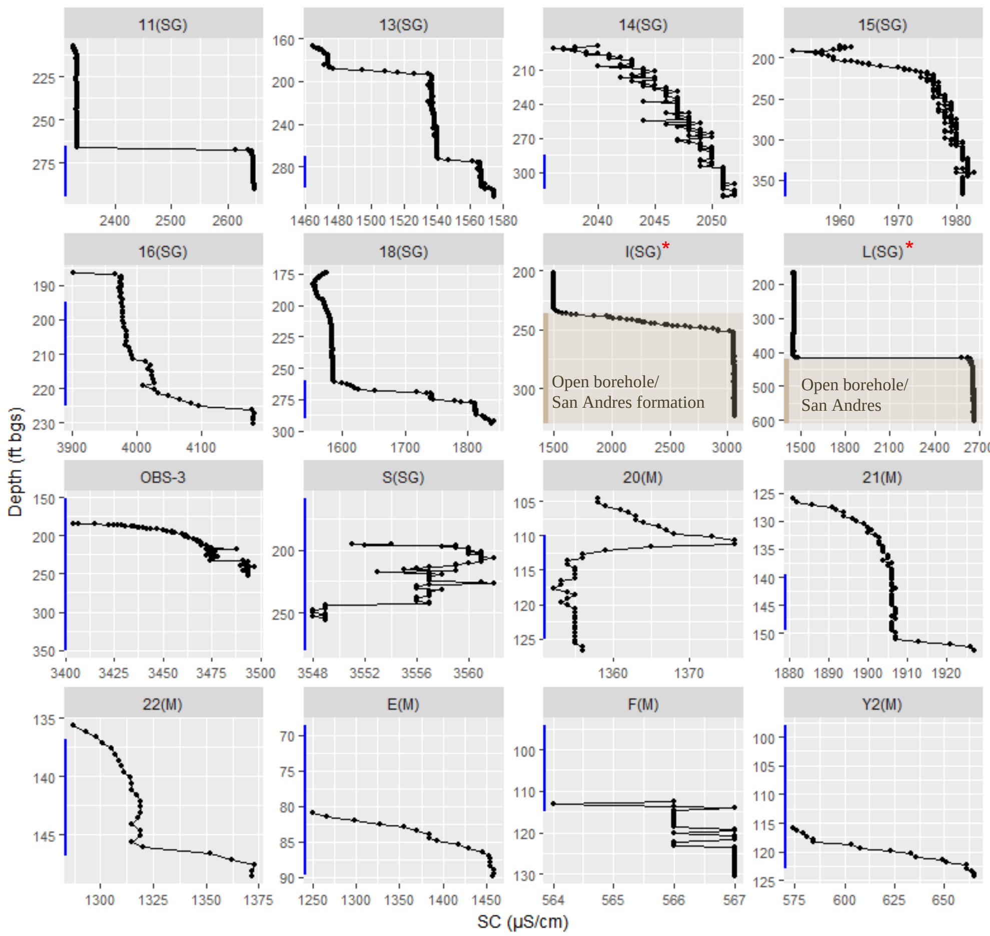
bgs below ground surface
CV coefficient of variation
μS/cm microsiemens per centimeter
SC specific conductance

Bluewater, New Mexico, Disposal Site: October 2014 SC Profile Results

Synopsis:

SC profiling was conducted at the Bluewater disposal site October 21–23, 2014. Sixteen wells were profiled—6 screened in the alluvial aquifer and 10 in the San Andres aquifer. In the figure below, wells screened in the San Andres aquifer, most named with an "(SG)" suffix, are shown first. Alluvial wells, identified with an "(M)" suffix, are shown last.

Of the 16 wells profiled at the Bluewater site, the two San Andres aquifer wells with open-borehole construction, L(SG) and I(SG), had notable variation in their SC profiles (CVs = 0.3). L(SG) is a background well, and I(SG) is the farthest downgradient well used to monitor the San Andres aquifer and also a point-of-exposure (POE) well at the site. Remaining Bluewater site wells that were profiled had low- to mid-range variation in SC as shown below.



| Screened interval
* Well with highly varying SC profile (CV ≥ 0.1)

Notes:
Shaded regions above denote the San Andres formation in the two wells with open-borehole construction, I(SG) and L(SG).
Complete SC profiles could not be obtained at two wells screened in the San Andres aquifer: OBS-3 and S(SG).

Figure A-1. Specific Conductance Profiles in Bluewater, New Mexico, Disposal Site Wells October 2014 Phase I Measurements

Durango, Colorado, Disposal Site: June 2014 SC Profile Results

Synopsis:

SC profiling was conducted at the Durango disposal site on June 25, 2014. Seven wells were profiled in the vicinity of the disposal cell. Four wells are completed in the uppermost aquifer (bedrock of the Cliff House Sandstone and the Menefee Formations: 0605 (upgradient), 0607, 0612, and 0621. Three wells are completed in the alluvium: upgradient well 0623, 0608, and 0618. Three of the seven wells at the site had high variation in the SC profiles: wells 0607, 0618, and 0621. In well 0607, SC more than doubles in the central portion of the screened interval.

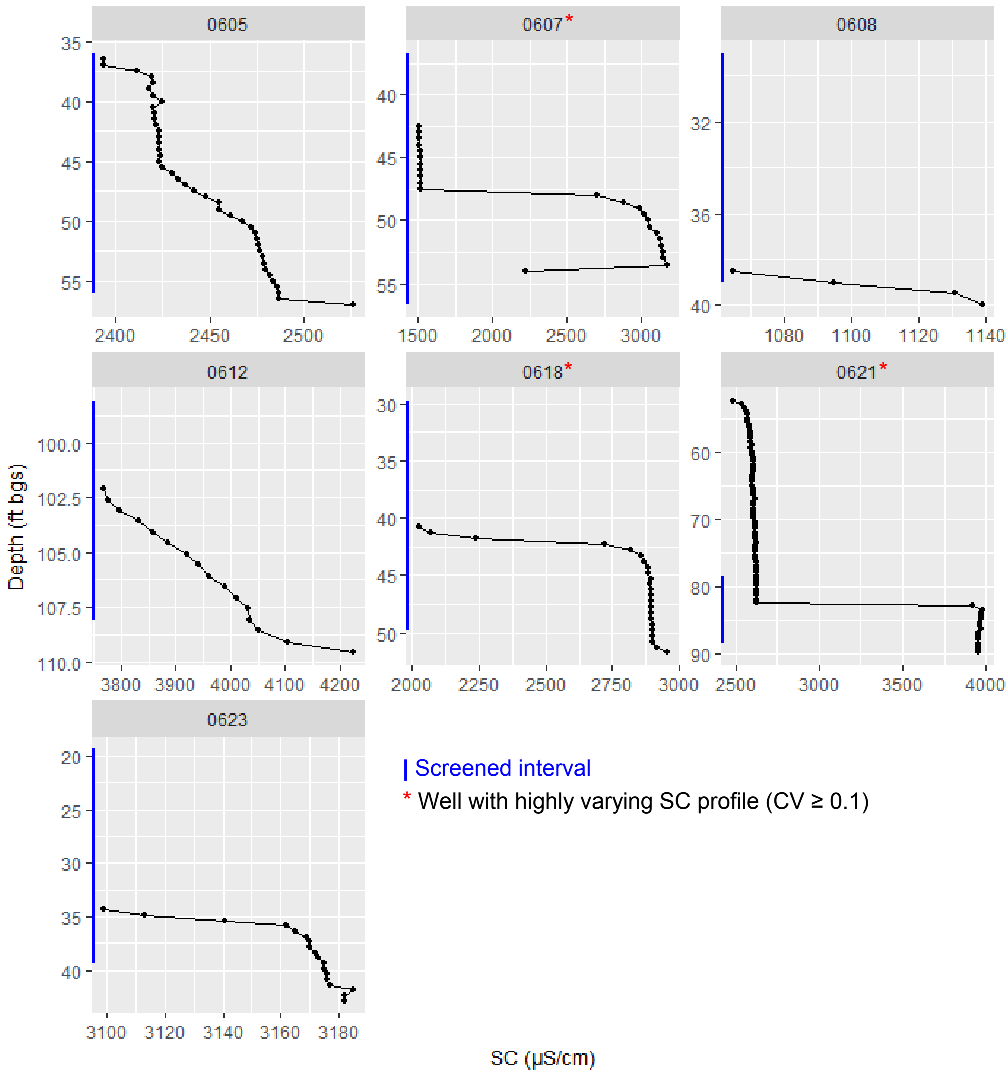


Figure A-2. Specific Conductance Profiles in Durango, Colorado, Disposal Site Wells June 2014 Phase I Measurements

Grand Junction, Colorado, Site: July-August 2013 SC Profile Results

Synopsis:

SC profiling was conducted at the Grand Junction site, one of the first sites to be profiled for this study, in July and August 2013. Eight alluvial wells were profiled. Six of the eight wells had very little variability in the SC profiles, with CVs ≤ 0.03. Two wells, 8-4S and 6-2N, had SC profiles with CVs of 0.1 or greater. Well 6-2N had a fairly high CV of 0.1 due to increases in SC in the uppermost part of the water column. However, SC measurements were homogeneous throughout the screened interval. In well 8-4S (CV = 0.22), SC increased markedly at the screen bottom–sump interface.

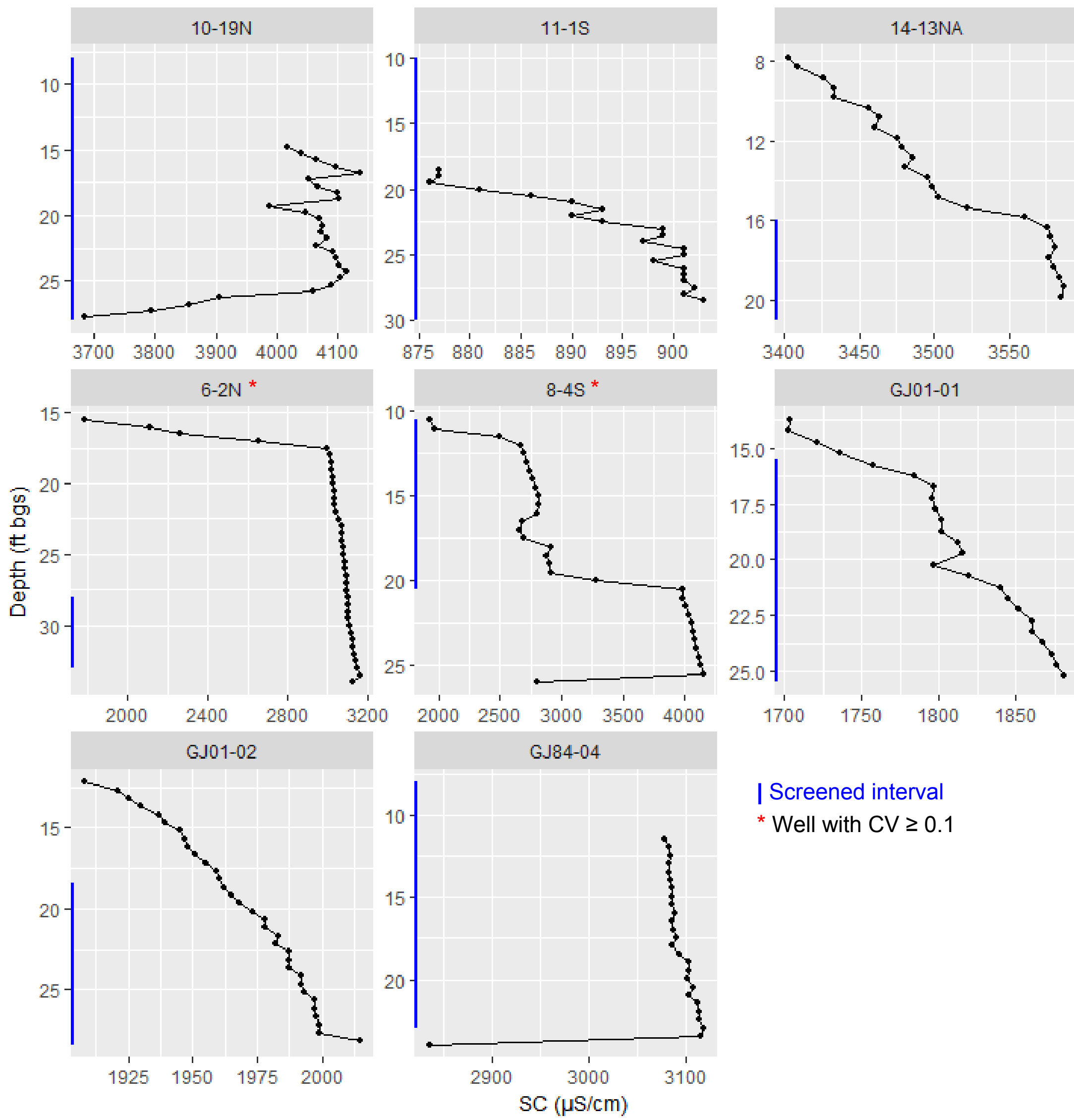


Figure A-3. Specific Conductance Profiles in Grand Junction, Colorado, Site Wells July–August 2013 Phase I Measurements

Grand Junction, Colorado, Processing Site: April 2014 SC Profile Results

Synopsis:

SC profiling was conducted at the Grand Junction processing site in April 2014 (this site is not regularly monitored). Only four alluvial wells were profiled: 0590, 0748, 1001, and 1036. These are the only existing wells at the site except for a Bureau of Reclamation well that was not accessible at the time of profiling. Only one well, 0748, had a highly varying SC profile (CV = 0.1). Although the CV for well 0590 indicated relatively low variation (CV = 0.03), the marked change in SC at the mid-screen interval is notable.

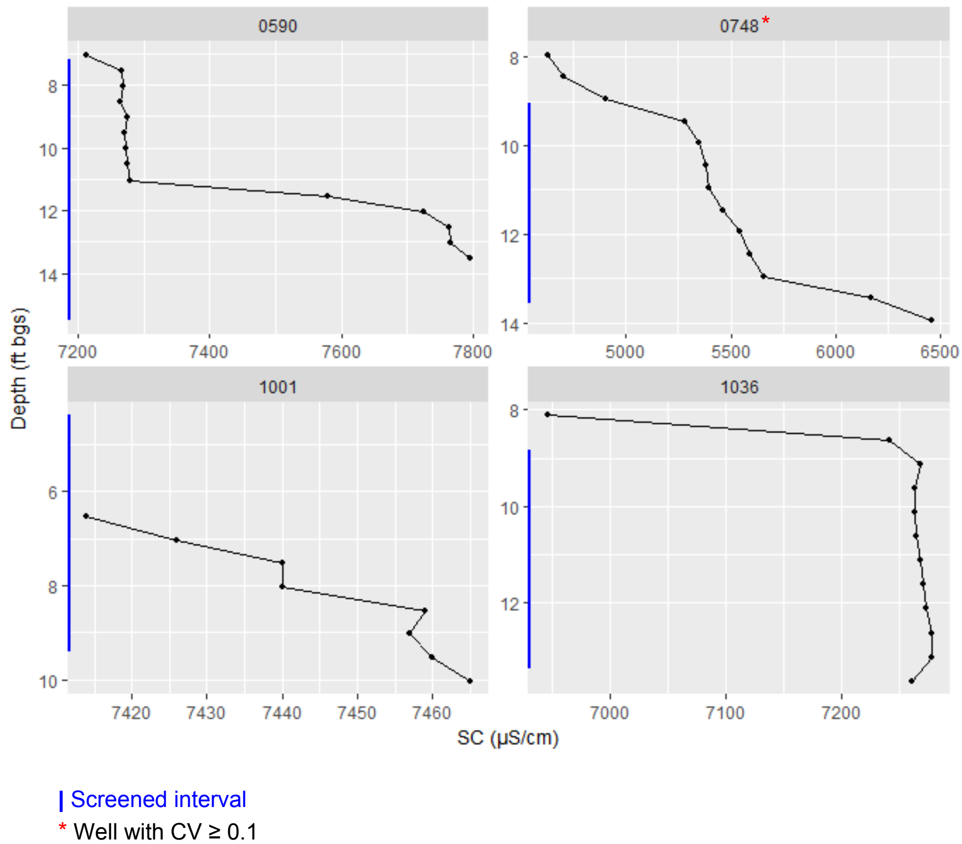


Figure A-4. Specific Conductance Profiles in Grand Junction, Colorado, Processing Site Wells April 2014 Phase I Measurements

Green River, Utah, Disposal Site: May 2014 SC Profile Results

Synopsis:

SC profiling was conducted at the Green River site in May 2014. Of the 20 wells profiled, three wells in the vicinity of the disposal cell had highly varying SC profiles (CVs ≥ 0.1): wells 0172 (CV = 0.55), 0174 (CV = 0.3), and 0181 (CV = 0.10). Of these wells, only well 0181, which is colocated with well 0172, is routinely sampled. Of the 20 wells profiled at this site, alluvial well 0194 near Browns Wash had the most saline groundwater, with SC on the order of 40,000 µS/cm (the CV for this profile was 0.08).

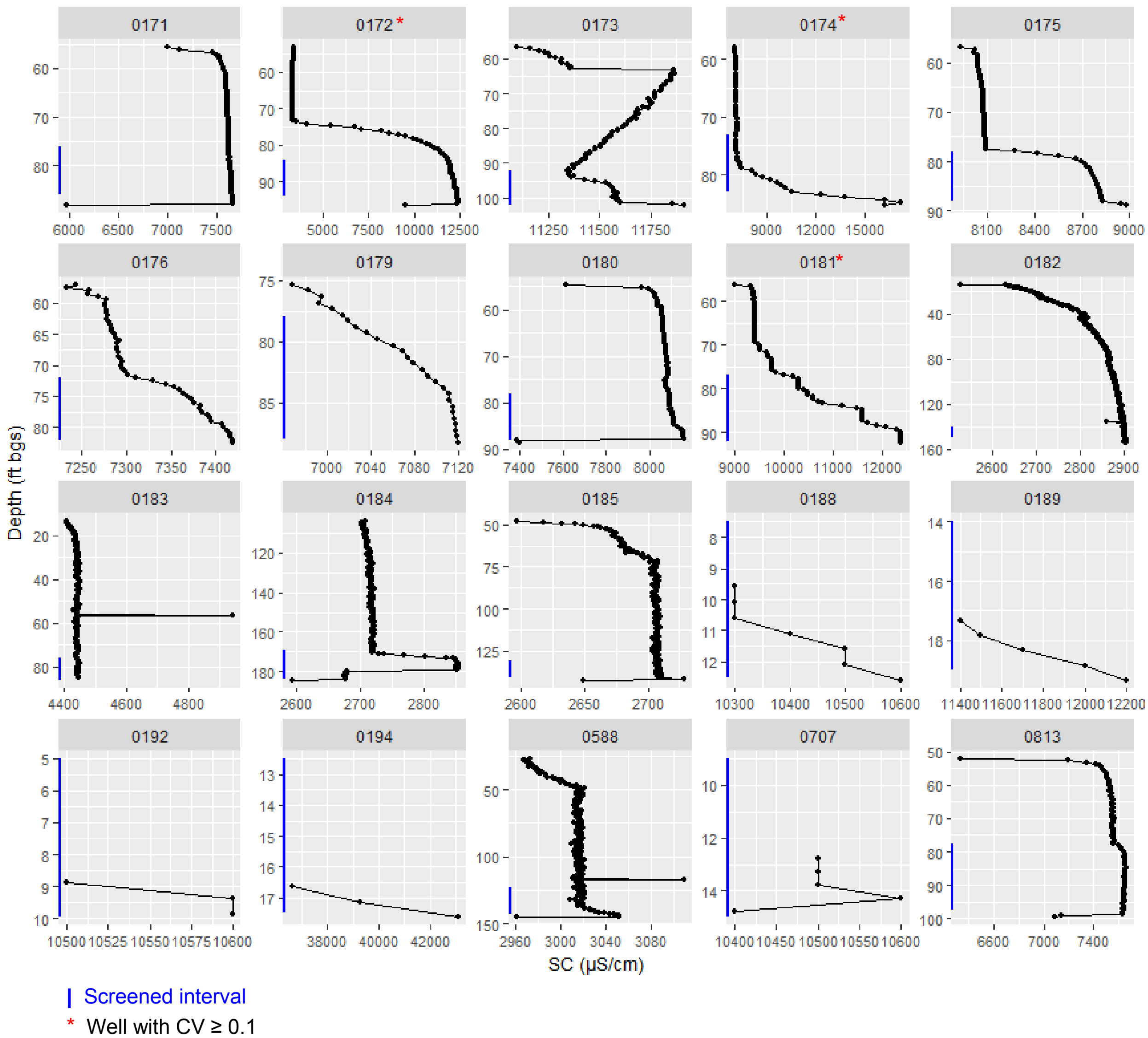
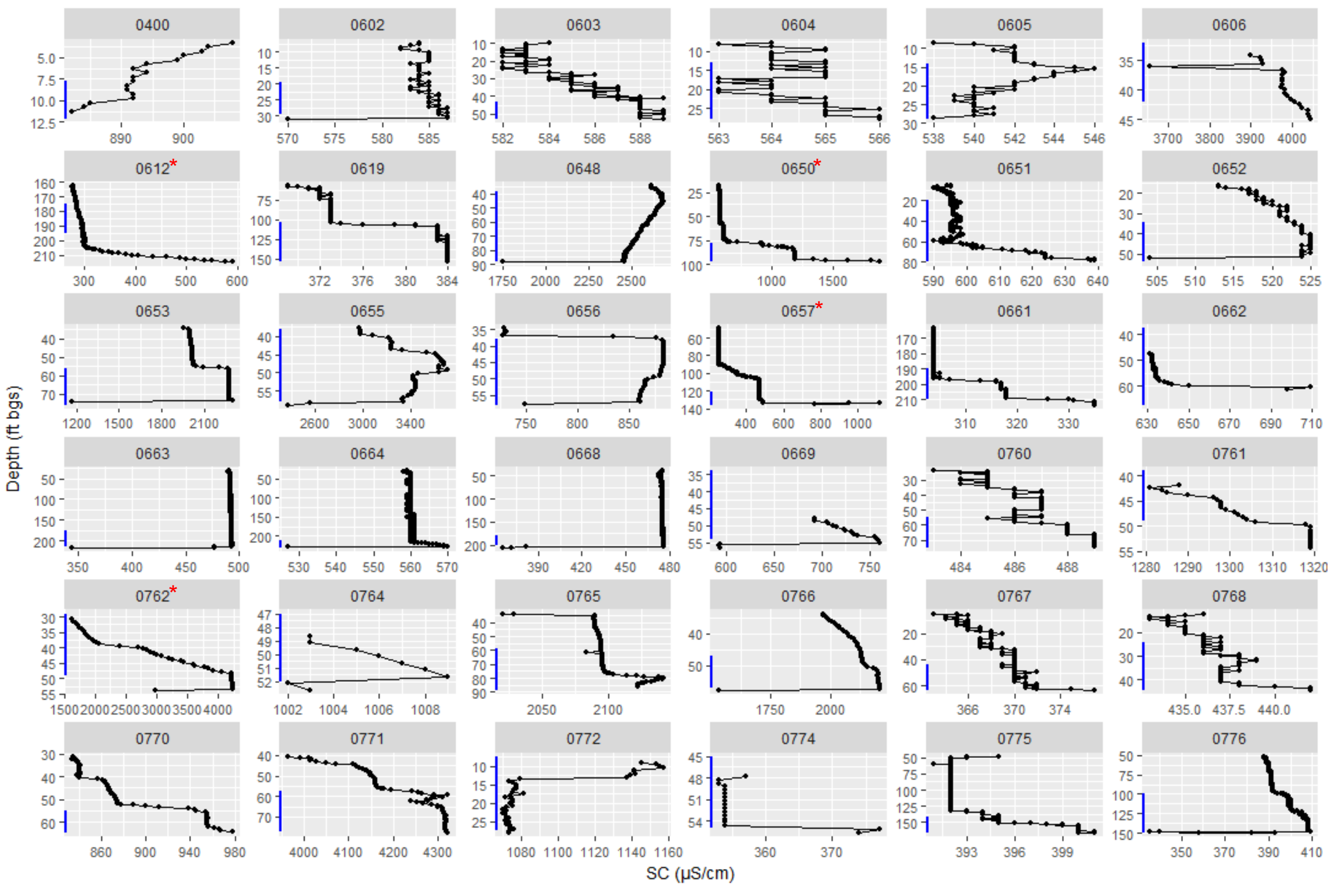


Figure A-5. Specific Conductance Profiles in Green River, Utah, Disposal Site Wells May 2014 Phase I Measurements

Monument Valley, Arizona, Processing Site: May–June 2014 SC Profile Results

Synopsis:

SC profiling was conducted at the Monument Valley processing site in May and June of 2014. Eighty-one wells were profiled: 63 screened in the alluvial aquifer, 12 in the DeChelly aquifer, and 6 in the Shinarump aquifer. Due to this large number of wells, only wells that are routinely sampled and that have screen information are shown in the figure below. The wells with the most highly varying SC profiles (with CVs ≥ 0.3) were 0650, 0657, and 0762. At far downgradient wells 0650 and 0762, the SC profile slope changed markedly within the screened interval, in particular at well 0762.



| Screened interval

* Well with CV ≥ 0.1

Note:

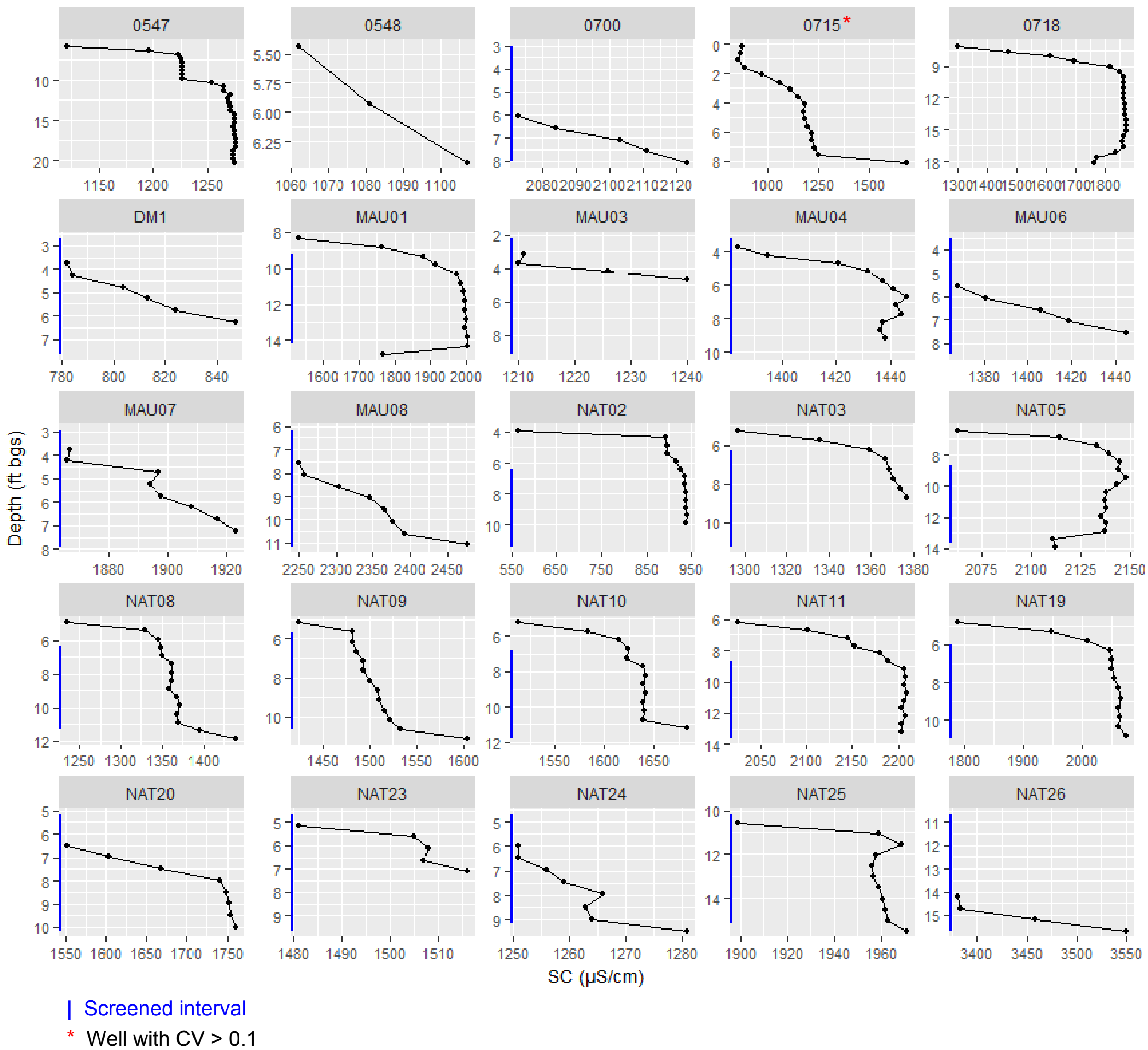
In the Phase I study, the CV was calculated using SC measurements over all well intervals. In some cases, wells described as having highly varying SC profiles had homogenous profiles within the screened interval.

Figure A-6. Specific Conductance Profiles in Monument Valley, Arizona, Processing Site Wells May–June 2014 Phase I Measurements

Naturita, Colorado, Processing Site: June 2014 SC Profile Results

Synopsis:

SC profiling was conducted at the Naturita processing site June 9–10, 2014; 26 alluvial wells were profiled. Most wells profiled, even those within the former tailings area and those close to the San Miguel River, had very little variation in the profiles. The most variable SC profile was measured in well 0715, for which screen information is not available.



Note:
Screen depth information is not available for wells 0547, 0548, 0715, and 0718.

Figure A-7. Specific Conductance Profiles in Naturita, Colorado, Processing Site Wells June 2014 Phase I Measurements

New Rifle, Colorado, Processing Site SC Profile Results

Synopsis:

SC profiling was conducted at the New Rifle processing site in July and October 2013. Forty-one wells were profiled, including 32 alluvial wells, 2 wells screened in the Wasatch Formation, and 7 City-owned wastewater treatment dewatering wells. This appendix only addresses results for 16 of the 41 wells, those that have been routinely sampled and also having screen information. Of the wells plotted in the figure below, three had notable variation (with CV > 0.1): 0172, 0215, and 0216. In remaining wells, SC varied, but only over a small range of measurements. Wells 0215 and 0216 have been key locations for monitoring flushing of the uranium plume in the main body of the site. Well 0172, coincides with the westernmost extent of the site's institutional controls boundary.

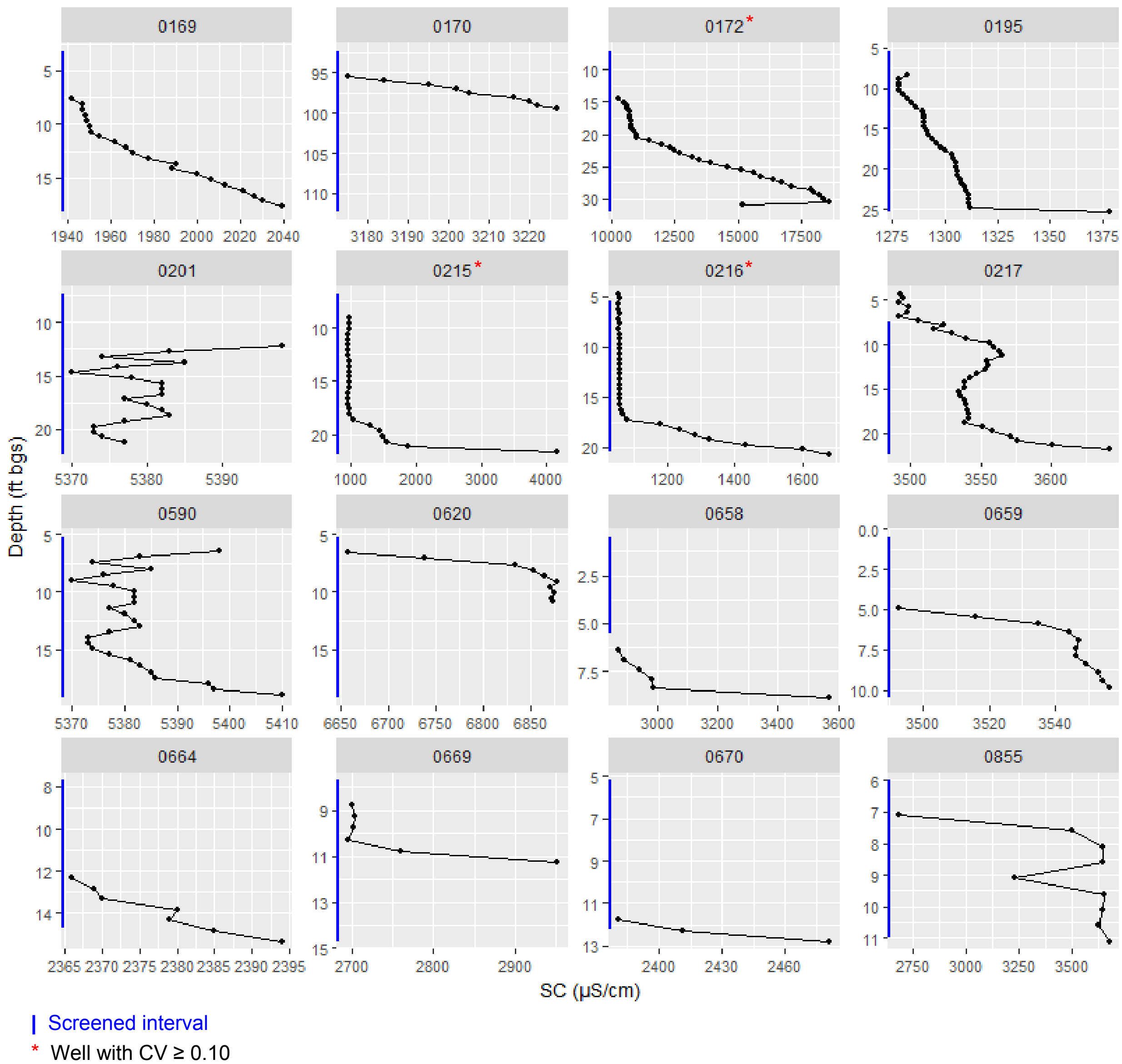


Figure A-8. Specific Conductance Profiles in New Rifle, Colorado, Processing Site Wells 2013 Phase I Measurements

Old Rifle, Colorado, Processing Site SC Profile Results

Synopsis:

SC profiling was conducted at the Old Rifle site in late October 2013. Twenty-two alluvial wells were profiled, including 2 background wells (0292A and 0658) and 10 wells used to monitor water chemistry under an Integrated Field Research Challenge (IFRC) program evaluating uranium biosequestration, sponsored by the DOE Office of Science. Figure A-9 (below) shows SC profile results only for the 12 wells monitored by LM. Overall, there was very little variation in most SC profiles at the Old Rifle site. The only well with notable variation in the SC vertical profile was well 0305 (CV = 0.19). This relatively high CV is attributed to the 3000 µS/cm outlier measurement at the bottom of the screened interval, which is also the bottom of the well.

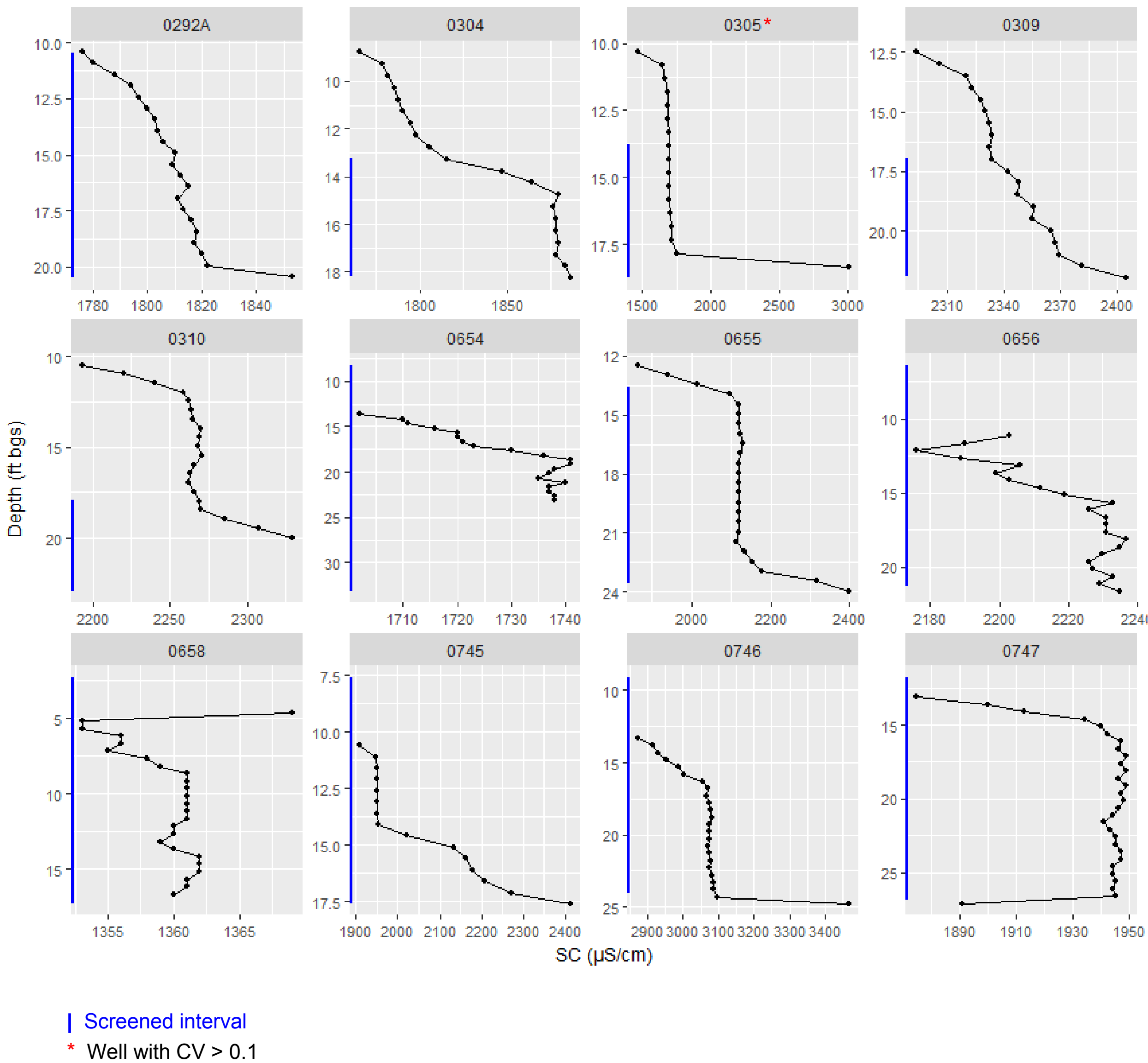
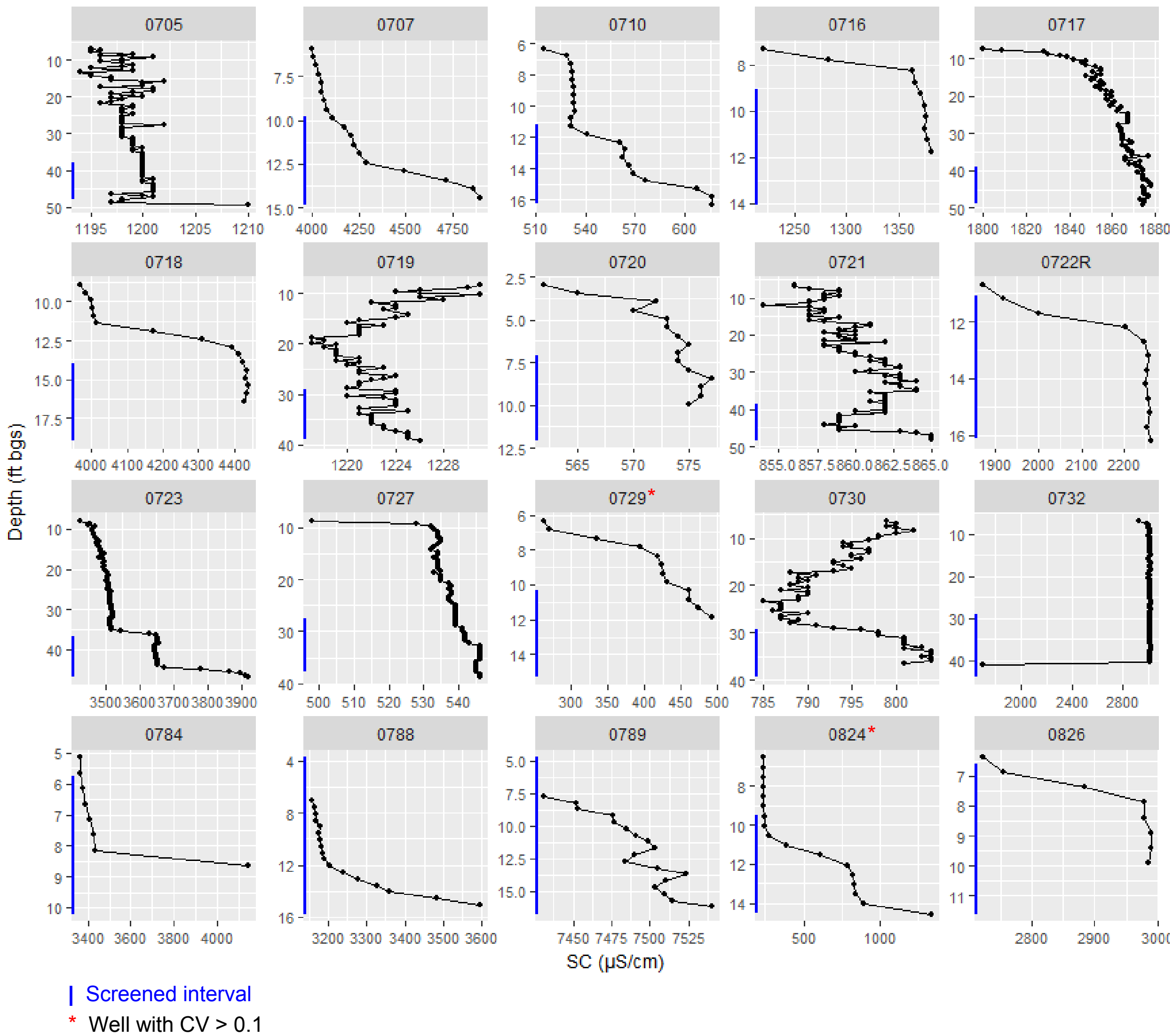


Figure A-9. Specific Conductance Profiles in Old Rifle, Colorado, Processing Site Wells October 2013 Phase I Measurements

Riverton, Wyoming, Processing Site SC Profile Results

Synopsis:

SC profiling was conducted at the Riverton processing site in September 2014. Thirty-three Riverton site wells were profiled: 17 surficial (alluvial) aquifer wells, 13 semiconfined aquifer wells, and three confined aquifer wells. Due to this large number of wells, only the 20 wells that are routinely sampled are shown in the plot of SC profile results below. Of these wells, only well 0824 had notable variation in the SC profile (CV = 0.67).



Note:
The profile in well 0729 was incomplete.

Figure A-10. Specific Conductance Profiles in Riverton, Wyoming, Processing Site Wells September 2014 Phase I Measurements

Slick Rock, Colorado, Processing Site (Slick Rock East): SC Profile Results

Synopsis:

SC profiling was conducted at the Slick Rock processing sites in June 2014. This site consists of two former uranium-ore processing facilities, referred to as the Slick Rock East (SRE) site and, approximately 1 mile downstream from SRE, the Slick Rock West (SRW) site. Both sites are located along the Dolores River in San Miguel County. Thirteen alluvial wells were profiled at the Slick Rock East site, including two background wells. Of these wells, five had notable variation in the SC profiles (with CVs ≥ 0.1). These wells are, in order of descending CV—0304, 0302, 0308, 0303, and 0300. Of these wells, only 0300 (the site background well), 0303, and 0309 are routinely sampled.

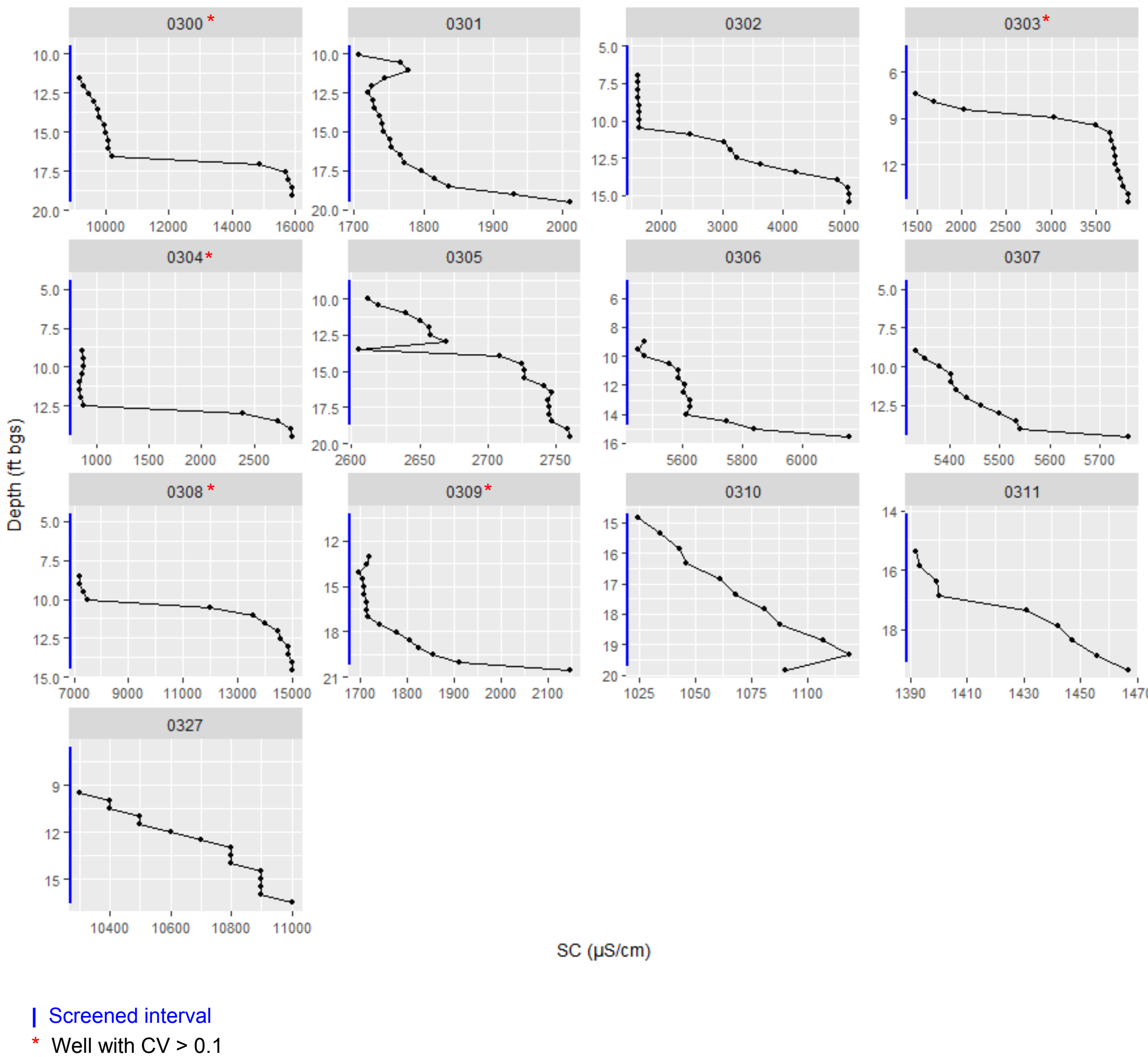


Figure A-11. Specific Conductance Profiles in Slick Rock East Processing Site Wells June 2014 Phase I Measurements

Slick Rock, Colorado, Processing Site (Slick Rock West): SC Profile Results

Synopsis:

SC profiling was conducted at the Slick Rock West processing site in June 2014. Of the 19 alluvial wells profiled at the site, two (wells 0319 and 0322) had notable variation in SC profiles (CVs ≥ 0.1). Only one of these wells, 0319, is routinely sampled.

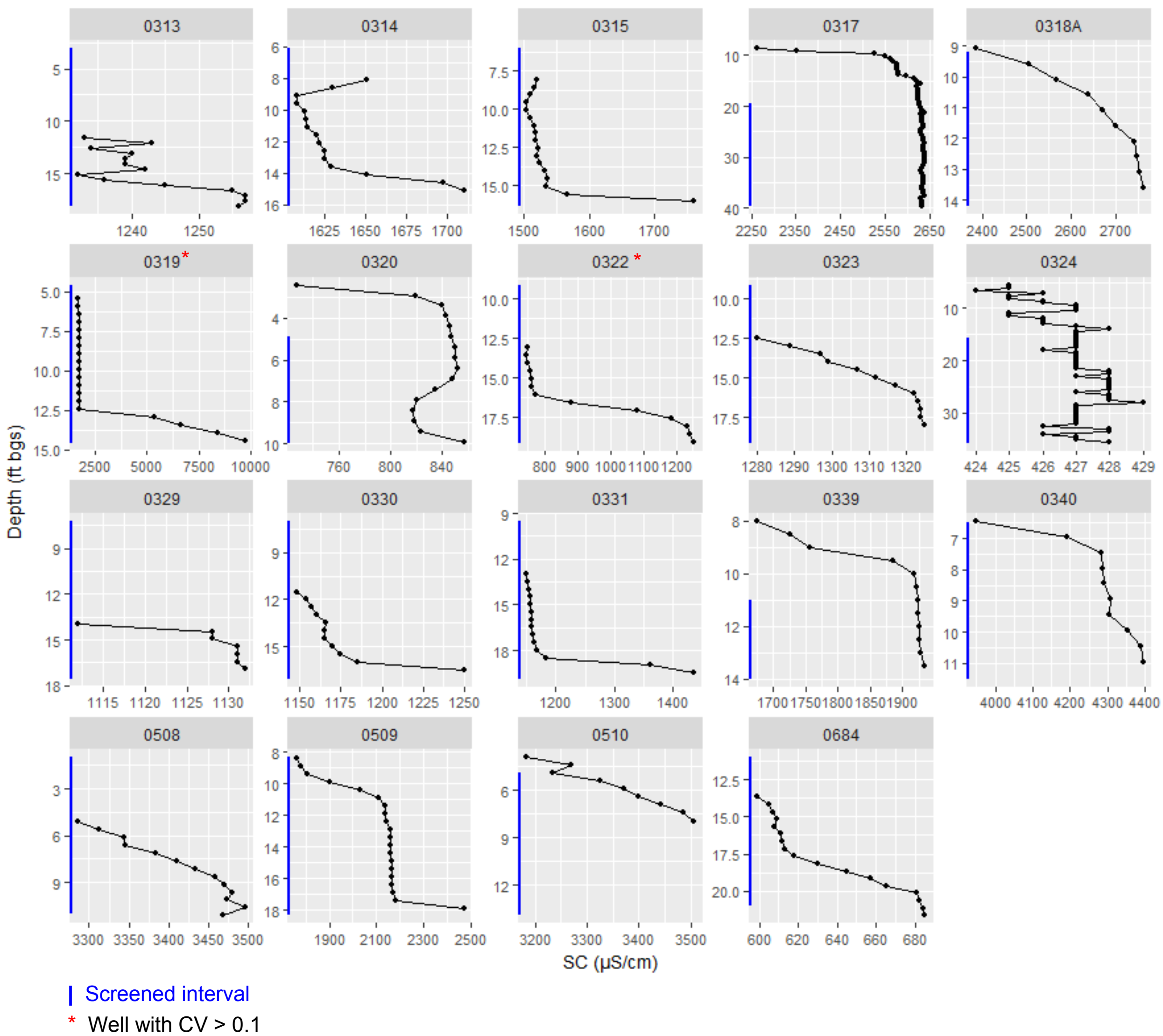


Figure A-12. Specific Conductance Profiles in Slick Rock West Processing Site Wells June 2014 Phase I Measurements

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Appendix B

Phase II Field Observations and Downhole Video Profile Results

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This appendix elaborates upon the summary material provided in Section 3 in the main body of this report, summarizing field observations made during Phase II profiling and sample collection, as well as screen depth measurement and observations during the downhole camera surveys. Downhole videos were conducted in the spring and summer following the chemical profiling—in April 2016 on the Shiprock site floodplain, and in June 2016 at the Durango processing site. The purpose of this effort was to verify screen placement and identify any mineralization or fouling that might cause restricted flow. Summaries are provided in tabular format.

B. 1 Durango Processing Site Mill Tailings Area

Table B.1.1 Summary of Field Observations, Durango Site Mill Tailings Area Wells August–September 2015 Phase II Sampling

Well	Comment
0617	Although this alluvial well was profiled for SC in Phase I, at the time of Phase II profiling, there was insufficient water to sample (only about 1 ft).
0629	At the time of profiling, the top of the water column was about 15 ft bgs, 6 ft below the top of the screened interval. During sampling, dissolved gas was observed in the samples, a factor that could have potentially impacted ^{222}Rn sample results. Radon-222 concentrations were low in this well, about 75 pCi/L.
0632	Screened solely in the Mancos Shale, well 0632 is a low-producing well. Due to difficulties in pumping and with sampling equipment during the Phase II profiling, it was necessary to deploy and redeploy the bladder pump 4 times. This may have caused some mixing of groundwater from different depths within the well during sampling. The low production and pumping during sampling resulted in significant (19 ft) drawdown in this well.
0633	Difficulty deploying the pump during profiling may have caused some mixing of groundwater from different depths in the well. Dissolved gas was observed in some samples, as was black threadlike material. Some samples also had a strong odor. A subsequent borehole video revealed a clump of roots at about 13 ft below the top of the casing.

Abbreviations:
bgs below ground surface
pCi/L picocuries per liter

Table B.1.2. Summary of Downhole Video Well Profiling of Durango Processing Site Mill Tailings Area Wells, July 19, 2016

				Screen Depths (ft btoc)						
		Elevation (ft amsl)		LM Database		DHV Survey Results		Differences		
Well	**ZOC**	**Surface**	**TOC**	**T_Scr**	**B_Scr**	**T_Scr**	**B_Scr**	**T_Scr Δ**	**B_Scr Δ**	**Observations**
0612 *	AL	6500.94	6499.21	39.14	59.14	38.75	57.4	-0.39	-1.74	Clean
0622	AL	6494.8	6492.91	10.89	15.89	9.7	14.85	-1.19	-1.04	Clean
0629	AL-KM	6507.75	6505.95	10.8	20.8	11.55	20.9	0.75	0.1	Clean
0630 *	AL-KM	6494.44	6492.91	29.83	39.83	30	39.35	0.17	-0.48	Clean
0631 *	AL-KM	6477.91	6475.93	7.98	17.98	7.7	17	-0.28	-0.98	Clean
0632	KM	6477.93	6476.12	52.81	57.81	53.6	?	0.79		Obscured visual from 57.4 ft btoc to TD @ 58.6 ft btoc
0633 *	AL-KM	6481.81	6478.75	7.06	17.06	7.3	?	0.24		Obscured visual from 16.3 ft btoc to TD @17.3 ft btoc
0634 *	AL-KM	6491.75	6489.53	10.22	20.22	10.35	19.6	0.13	-0.62	Clean
0635 *	AL	6497.68	6495.92	7.26	17.26	7.75	17	0.49	-0.26	Clean
0857	AL	6490.08	6487.47	14.61	19.61	15.5	19.9	0.89	0.29	Clean
0859	AL	6490.58	6490.89	21.19	31.19	22	31.5	0.81	0.31	Clean
0863 *	CV	6513.32	6513.56	57.76	67.26	58.3	67.8	0.54	0.54	Clean
0866	AL	6483.32	6481.15	14.17	23.67	14.2	23.7	0.03	0.03	Clean

Notes:

–1.74 Denotes greater than 1-ft discrepancy between downhole video (DHV) profile results and well construction log. DHV indicates higher (more shallow) screen placement than that indicated in well construction log.

Abbreviations:

*	denotes well routinely sampled
amsl	above mean sea level
AL	alluvium
B_Scr	bottom of screen depth
btoc	below top of casing
CV	Colluvium
DHV	downhole video
ft	feet
KM	Mancos Shale
TOC	top of casing
TD	total (well) depth
T_Scr	top of screen depth
ZOC	Zone of completion
Δ	difference between well construction log and downhole video survey results

B. 2 Durango Processing Site Raffinate Ponds Area

Table B.2.1 Summary of Field Observations, Durango Processing Site Raffinate Ponds Area Wells August–September 2015 Phase II Sampling

Well	Comment
0593	Accumulation of black material on the pump intake may have caused the slow pumping rates in this well. Small air bubbles were observed in samples collected for ^{222}Rn analysis.
0594	Using a peristaltic pump, pumping rates were slow (~40 mL/min), potentially the cause of air bubbles in some samples. This excess air made ^{222}Rn sample collection difficult and precluded the collection of a ^{222}Rn sample at 22 ft btoc.
0598	At this well, it was difficult to deploy the pump past 75 ft btoc (corresponding to the Bodo Fault Zone), and it was not possible to deploy it beyond about 85 ft bgs. Initial attempts to deploy and re-deploy the pump beyond that point might have resulted in some mixing of the water. The sample tubing was cut several times during interval sampling to decrease the purge volume required between samples. During later downhole video profiling, no obstruction was observed (the well appeared to be clean).
0875	Similar to the situation described for well 0598 above, the pump had to be deployed several times (first apparent obstruction at about 85 ft btoc). It was not possible to deploy the pump beyond 112 ft of this 120 ft well. This well had significant drawdown, and black particulate material accumulated in the pump intake screen.
0879	The July 2016 downhole video revealed an obstruction at 30.6 ft btoc (approximate mid-screen interval); no visual of the screen could be obtained.
0884	Sampling initiated using a peristaltic pump, but due to excessive air in the samples, a bladder pump was used. All samples except the lowermost ones (below 45 ft btoc) were collected using a bladder pump.
0889	Low producing well, a factor that resulted in significant drawdown. Once noticed, SC was measured in the purge water between samples, and it was observed that the conductivity in the purge water was lower than what was measured at that depth during the profile. This might indicate some mixing of the water in the well during pump deployment.
0883	Pumping rates were slow in this well (about 30–40 mL/min) at 40 ft btoc, attributed to a collection of black hairlike particulate on the pump intake. Another low producing well with significant drawdown. Because of this drawdown, it is possible that the water initially profiled for SC at a given depth may not be representative of water at that same depth at the time samples for chemical analysis were collected. As such, assessment of correlations between SC and chemical or other parameters for this well may not be valid.
0903	During SC profiling, it was possible to advance the sonde to a depth of 67.1 ft btoc (apparent bottom of the well). However, during sampling, the bladder pump could not be advanced beyond 57 ft btoc. Based on a later downhole video profile, this depth corresponds to the location of a joint in the pipe/casing.

Abbreviations:

^{222}Rn radon-222
bgs below ground surface
btoc below the top of the casing
mL/min milliliter(s) per minute
SC specific conductance

Table B.2.2 Summary of Observations Made During Downhole Video Well Profiling, Durango Former Raffinate Ponds Area Wells, July 19, 2016

				Screen Depths (ft btoc)						
		Elevation (ft amsl)		LM Database		DHV Survey Results		Differences		
Well	**ZOC**	**Surface**	**TOC**	**T_Scr**	**B_Scr**	**T_Scr**	**B_Scr**	**T_Scr Δ**	**B_Scr Δ**	**Observations**
0593	MF	4890.34	4892.93	18.9	38.9	14.3	33.8	-4.6	-5.1	Clean
0594 *	MF	4890.03	4892.56	8.6	38.6	8.7	38.2	0.1	-0.4	Clean
0598 *	FM-FP	4888.81	4891.41	70.2	100.2	68	96.8	-2.2	-3.4	Clean
0607 *	AL-MF	4891.38	4893.5	36	56	34.7	55	-1.3	-1	Clean
0875	PL	4891.37	4893.68	83.61	123.61	83.6	122.8	-0.01	-0.81	Clean
0879 *	MF	4890.29	4892.1	27.01	36.91	?	?			Obstruction at 30.6 ft btoc; no visual of screen
0882	MF	4889.27	4891.23	26.4	36.4	28.1	37.6	1.7	1.2	Clean
0883	MF	4891.64	4894.34	47.39	57.39	45.3	55	-2.09	-2.39	Clean
0884 *	MF	4890.83	4892.23	36.56	46.56	37	46.6	0.44	0.04	Clean
0889	PL	4889.67	4892.4	81.75	91.75	80.9	90.4	-0.85	-1.35	Clean
0903 *	MF	4887.9	4889.85	37.06	67.06	37.2	66.6	0.14	-0.46	Clean

Notes:

–4.6 Denotes greater than 1-ft discrepancy between downhole video (DHV) profile results and well construction log. DHV indicates higher (more shallow) screen placement than that indicated in well construction log.

1.7 Denotes greater than 1-ft discrepancy between DHV profile results and well construction log. DHV indicates deeper screen placement than that indicated in well log.

Abbreviations:

* denotes well routinely sampled

amsl above mean sea level
AL alluvium
B_Scr bottom of screen depth
btoc below top of casing
DHV downhole video
FM Fault - Cretaceous Menefee Formation
FP Fault - Cretaceous Point Lookout Sandstone
MF Cretaceous Menefee Formation
PL Cretaceous Point Lookout Sandstone
TOC top of casing
T_Scr top of screen depth
ZOC Zone of completion
Δ difference between well construction log and downhole video survey results

B.3 Shiprock Site Floodplain Well Profiling

Apart from air bubbles observed in several samples collected for ^{222}Rn analysis (wells 0614, 1013, and 1105), no major deviations were observed during the SC and chemical profiling. Table B.3.1 summarizes the downhole video profiles taken in April 2016.

Table B.3.1 Summary of Observations Made During Downhole Video Well Profiling, Shiprock Site Floodplain Wells, April 18–20, 2016

						Screen Depths (ft btoc)				
						DHV Survey Results				
Well		**Sampled?**	**ZOC**	**Area/Group**	**DHV Date**	**T_Scr**	**B_Scr**	**T_Scr Δ**	**B_Scr Δ**	**Observations**
0610		Yes	AL	Base of Escarpment	4/19/2016	6.4	11.4	-1.06	-1.06	Clean
0611		Yes	AL-KM	Base of Escarpment	4/19/2016	11.1	15.5	-1.67	-2.27	Clean
0612		Yes	AL	Hyporheic Wells	4/19/2016	7	11.5	0.56	0.06	Clean
0614		Yes	AL-KM	Base of Escarpment	4/19/2016	12	16.5	-0.49	-0.99	Clean
0618		Yes	AL	Central FP	4/20/2016	13	17.5	0.36	-0.14	Clean
0619		Yes	AL	Central FP	4/20/2016	10	14.5	0.23	-0.27	Clean
0622		Yes	AL	Central FP	4/20/2016	6.6 first visual	11.5		-0.05	Obscured visual
0626		Yes	AL	Western FP	4/20/2016	11.1	15.8	-1.32	-1.62	Clean
0628		Yes	AL	Western FP	4/20/2016	6.7 first visual	11.6		-0.43	Obscured visual
0630		Yes	AL	Western FP	4/20/2016	7.2 first visual	11.8		1.83	Obscured visual
0735		Yes	AL	Base of Escarpment	4/19/2016	6.2	10.5	1.88	1.18	Clean
1008		Yes	AL	Well 1089 Area	4/18/2016	9	18.7	0.02	-0.28	Clean
1009		Yes	AL	Hyporheic Wells	4/19/2016	9.5	19.3	0.29	0.09	Clean
1105		Yes	AL	Trench 1 Qal	4/19/2016	7.9	17	0.67	-0.23	Clean
1111		Yes	AL	Trench 1 Qal	4/19/2016	5.4	?	-3.55		Obscured visual
1115		Yes	AL	Trench 2 BOE	4/19/2016	8.7	13.5	-0.49	-0.69	Clean
1134		Yes	AL	Trench 2 East	4/19/2016	10.9	14.9	0.19	-0.81	Clean
1135		Yes	AL	Western FP	4/20/2016	9.8 first visual	14.3		0.08	Obscured visual
1136		Yes	AL	Central FP	4/20/2016	9.5	14.2	-0.12	-0.42	Clean
1137		Yes	AL	Well 1089 Area	4/18/2016	12.75	17.3	0.68	0.23	Clean
1138		Yes	AL	Well 1089 Area	4/18/2016	11.2	15.8	0.47	0.07	Clean
1139		Yes	AL	Well 1089 Area	4/18/2016	8.5	13.75	-0.65	-0.4	Clean
1141		Yes	AL	Trench 1 Qal	4/19/2016	7.8	12.2	-0.43	-1.03	Clean
1143		Yes	AL	Western FP	4/20/2016	11.7 first visual	?			Obscured visual
0613	*	not sampled	AL	Base of Escarpment	4/19/2016	7.5	11.9	-0.77	-1.37	Clean
0617	*	not sampled	AL	Central FP	4/20/2016	7.1	11.5	0.25	-0.35	Clean
0620	*	not sampled	AL-KM	Central FP	4/20/2016	14.9 first visual	?			Obscured visual
0621	*	not sampled	AL	Central FP	4/20/2016	?	?			Obscured visual
0627	*	not sampled	AL	Western FP	4/20/2016	?	?			Obscured visual
0629	*	not sampled	AL-KM	Western FP	4/20/2016	11.8	16.5	1.6	1.3	Obscured visual
1010	*	not sampled	AL	Central FP	4/20/2016	5.9	20.5	0.08	-0.32	Clean
1013	*	not sampled	AL-KM	Hyporheic Wells	4/19/2016	9.1	23.8	0.14	-0.16	Clean
1126	*	not sampled	AL	Trench 2 BOE	4/19/2016	9.8	14.2	0.23	-0.37	Clean
1127	*	not sampled	AL	Trench 2 East	4/19/2016	15.5 first visual	?			Obscured visual

Notes:

–4.6 Denotes greater than 1-ft discrepancy between downhole video (DHV) profile results and well construction log. DHV indicates higher (more shallow) screen placement than that indicated in well construction log.

1.7 Denotes greater than 1-ft discrepancy between DHV profile results and well construction log. DHV indicates deeper screen placement than that indicated in well log.

Abbreviations:

*	denotes well *not* routinely sampled
AL	alluvium
B_Scr	bottom of screen depth
btoc	below top of casing
DHV	downhole video
KM	Mancos Shale
T_Scr	top of screen depth
ZOC	Zone of completion
Δ	difference between well construction log and downhole video survey results

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Appendix C

Durango Processing Site Mill Tailings Area SC and Analyte Profiles

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Preface

Phase II of this study yielded 203 analyte profiles for the Durango processing site mill tailings area alone (13 wells × 15 parameters + 8 ^{222}Rn profiles). The discussion in the main body of the report focused mainly on SC, uranium, sulfate, and ^{222}Rn and on those wells with the most variable or interesting profiles. This appendix provides a comprehensive graphical summary of Phase II results for all mill tailings area well-variable combinations.

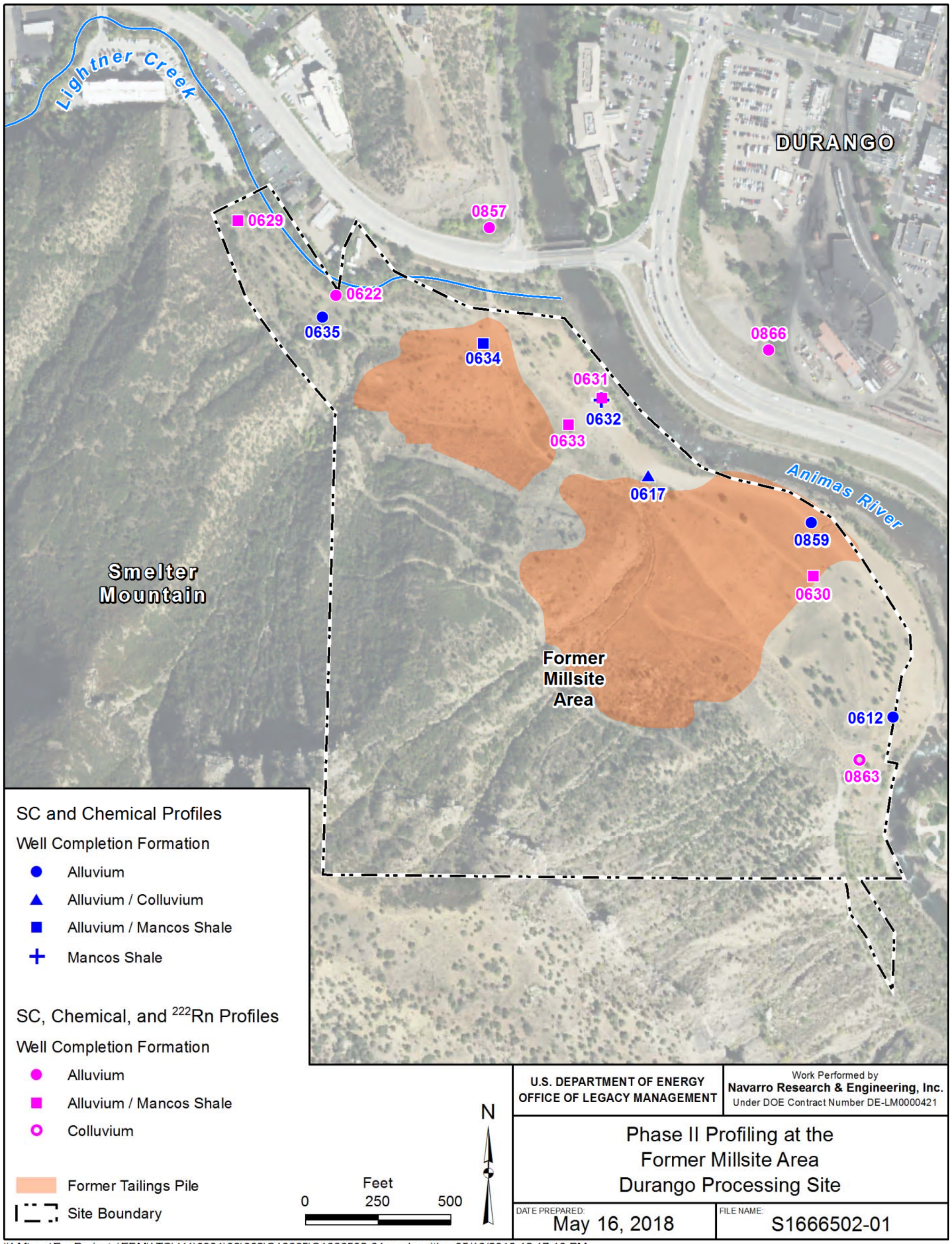
Appendix C-1 plots the profiles by variable, by well. For a given analyte, this presentation allows comparison of profiles between wells. Appendix C-2 provides a different view, plotting profiles of all parameters for each well. When interpreting these figures, it is important to acknowledge the range in values because scales are unique for each well- and variable-specific profile. As such, some profiles initially appearing as being highly variable may just represent random variation if the range of measurements is small. Because this appendix is intended as a stand-alone summary of all Phase II results, some figures from the main body of the report are duplicated. Legend items and abbreviations used globally are listed below.

Legend Items:

|	Screened interval
·····	Bedrock contact
▭	Mancos Shale
*	Routinely sampled well
○	BDL result

Abbreviations:

AL	alluvium
BDL	below detection limit (denoted by ○ in plots)
bgs	below ground surface
DOC	dissolved organic carbon
Fe	iron
KM	Mancos Shale
MCL	maximum concentration limit established in 40 CFR 192
mg/L	milligrams per liter
µS/cm	microsiemens per centimeter
SC	specific conductance
TOC	total organic carbon



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Note: Northernmost wells 0622, 0629, and 0857 and well 0866 are considered background wells for this area of the site. Figure duplicated from Figure 9 of the main text.

Durango Processing Site Mill Tailings Area Wells Profiled in Phase II

Appendix C-1

Vertical Profiles by Analyte

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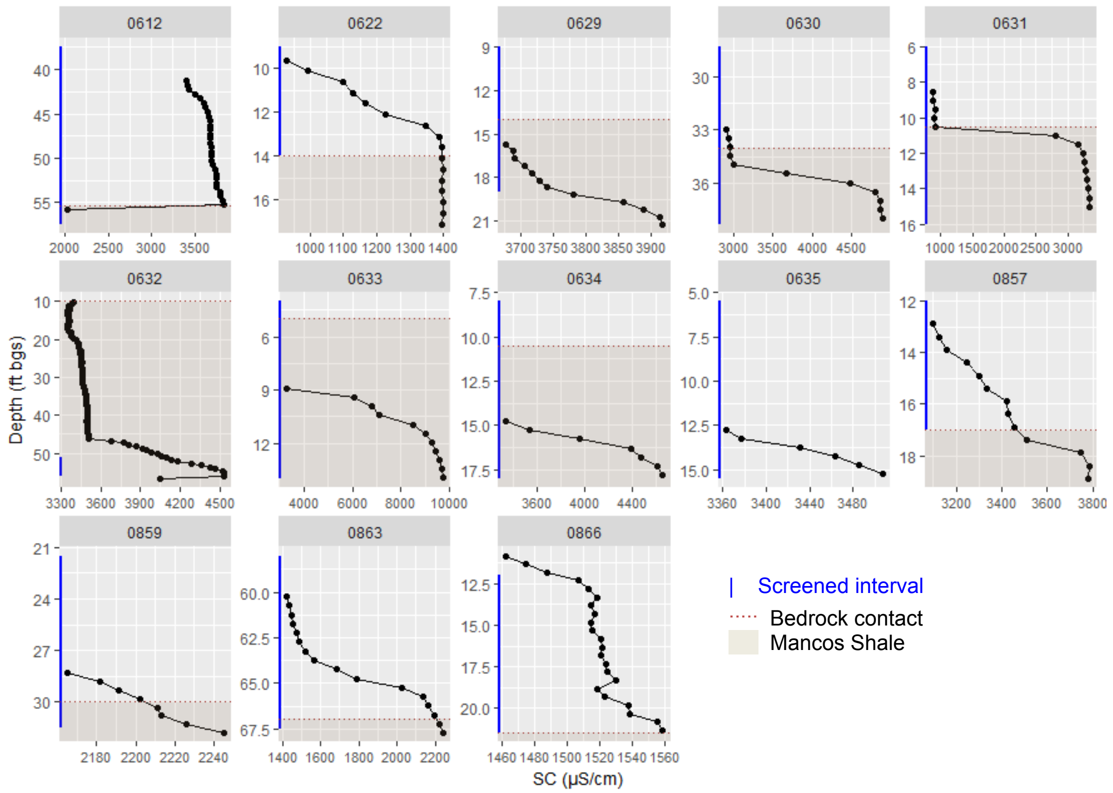

Figure C.1-1. Phase II Specific Conductance Profiles in Mill Tailings Area Wells

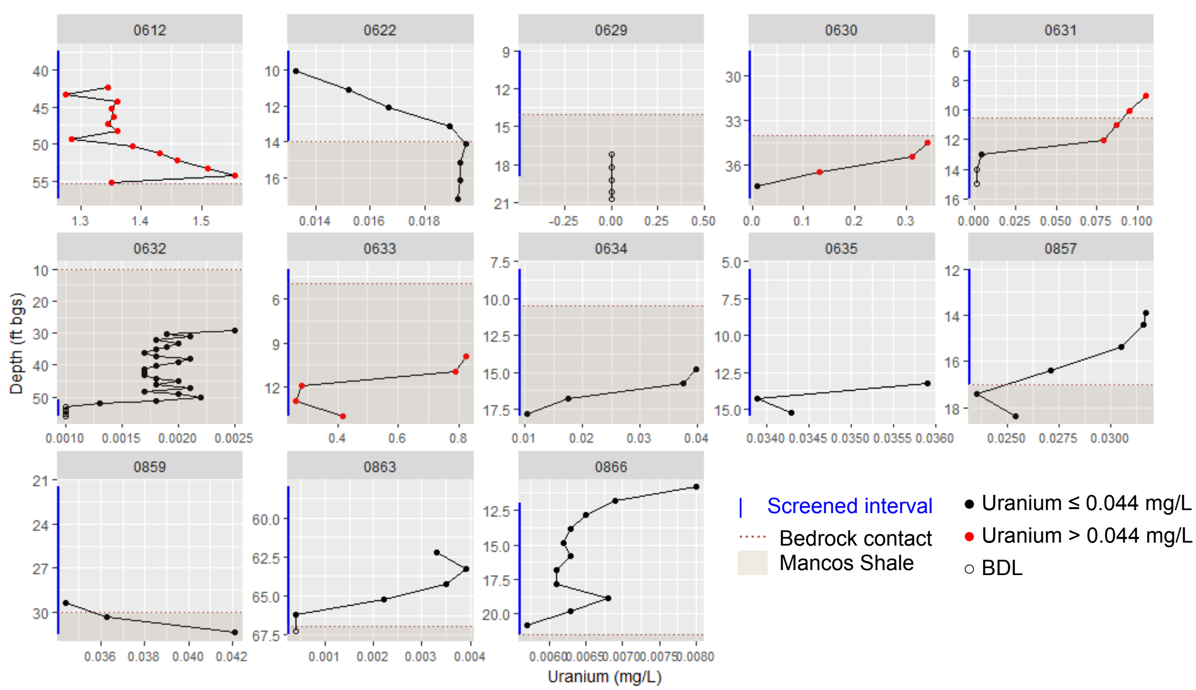

Figure C.1-2. Uranium Profiles in Mill Tailings Area Wells

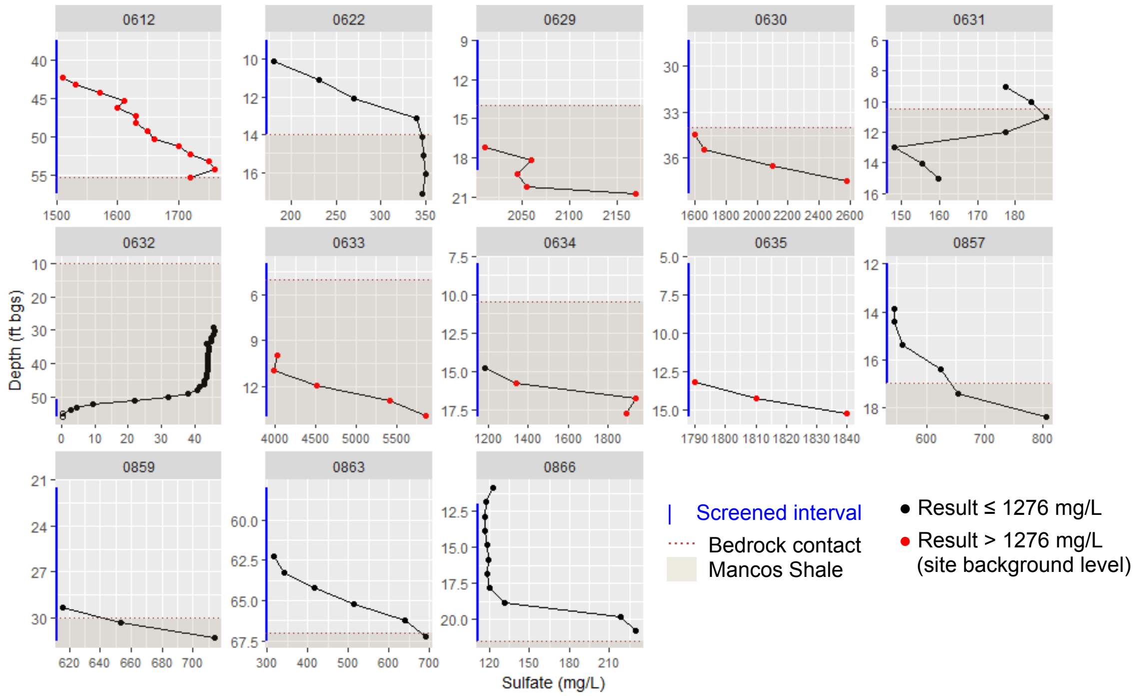

Figure C.1-3. Sulfate Profiles in Mill Tailings Area Wells

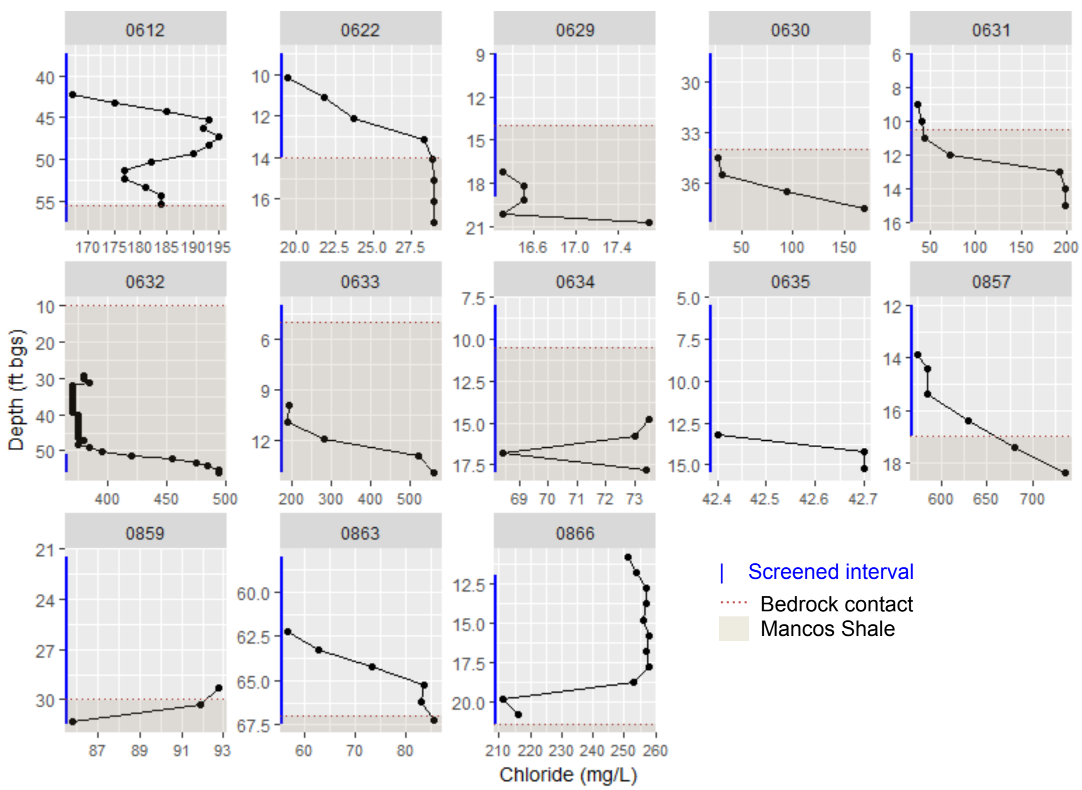

Figure C.1-4. Chloride Profiles in Mill Tailings Area Wells

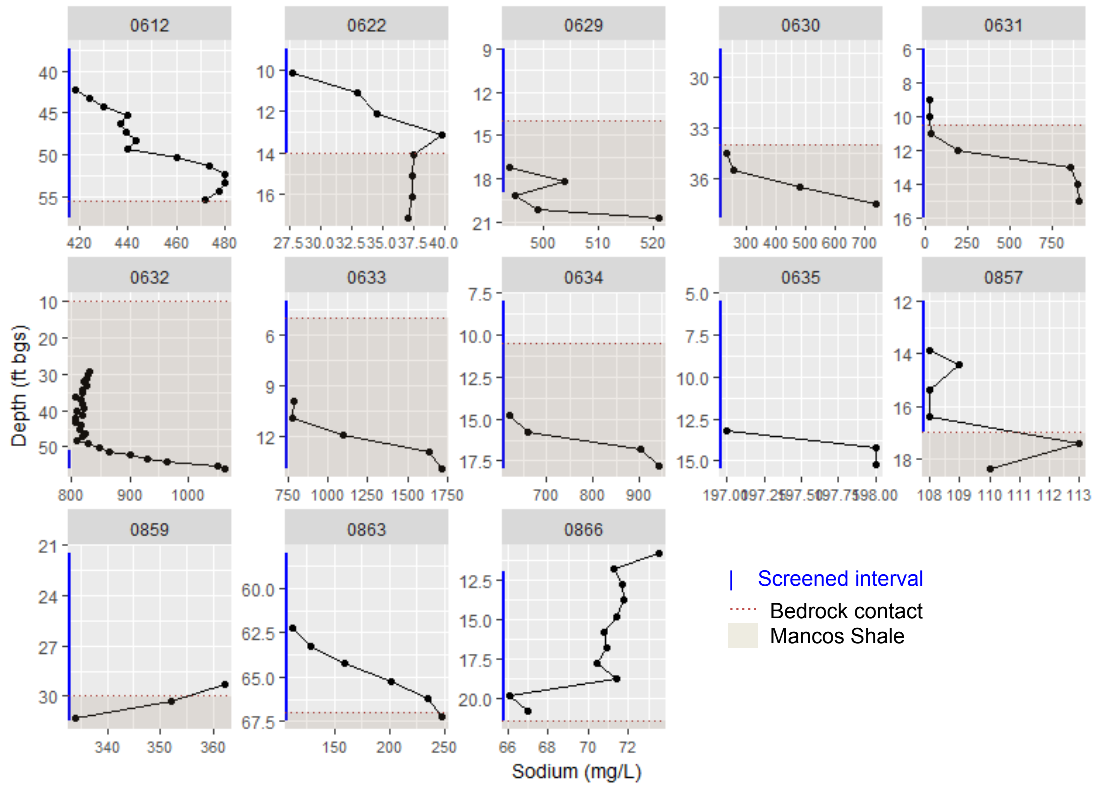

Figure C.1-5. Sodium Profiles in Mill Tailings Area Wells

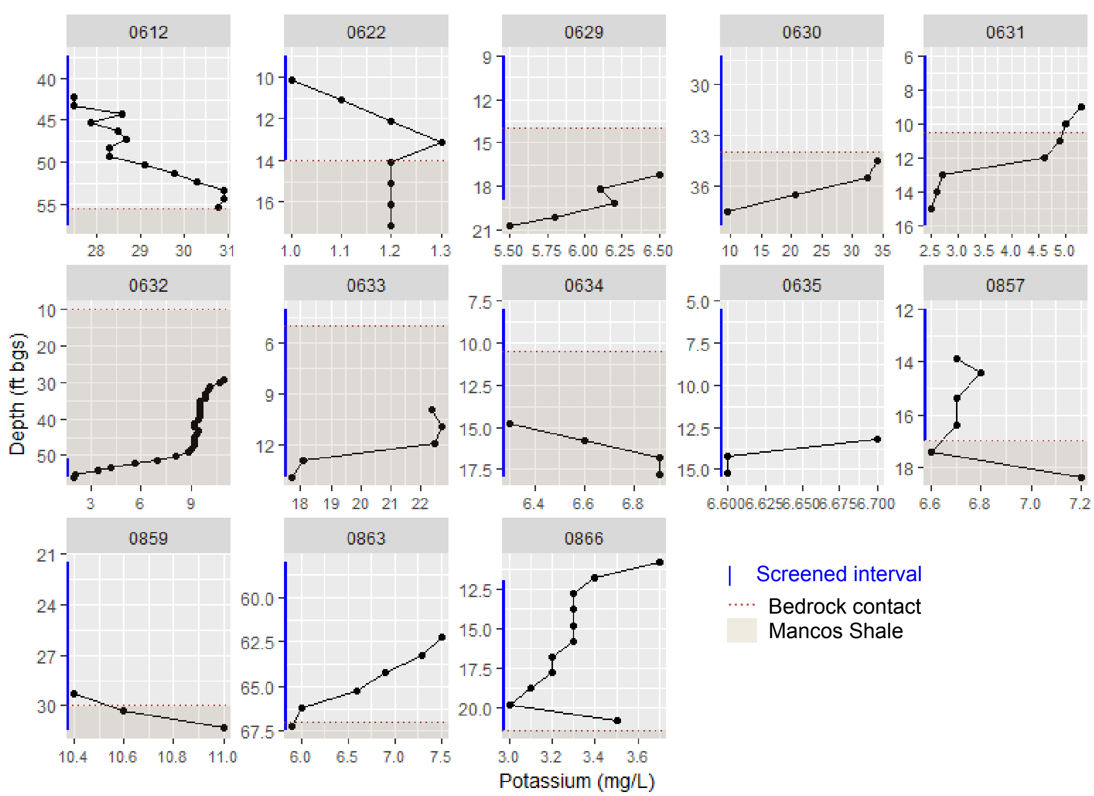

Figure C.1-6. Potassium Profiles in Mill Tailings Area Wells

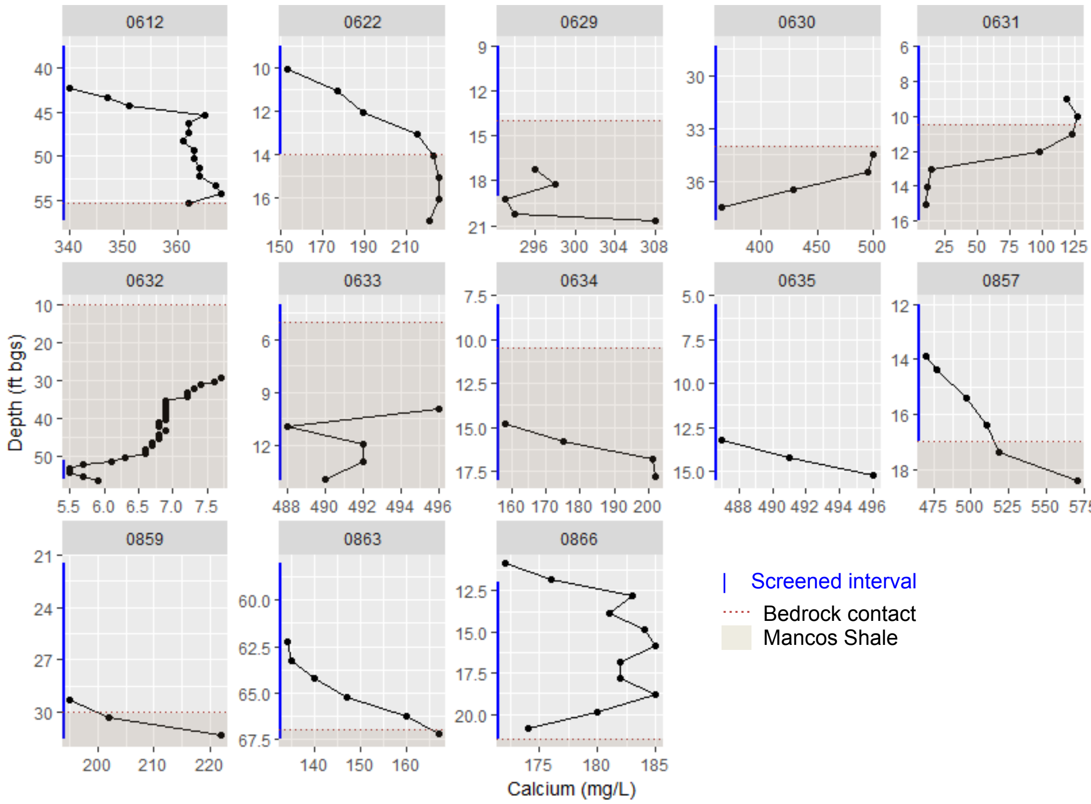

Figure C.1-7. Calcium Profiles in Mill Tailings Area Wells

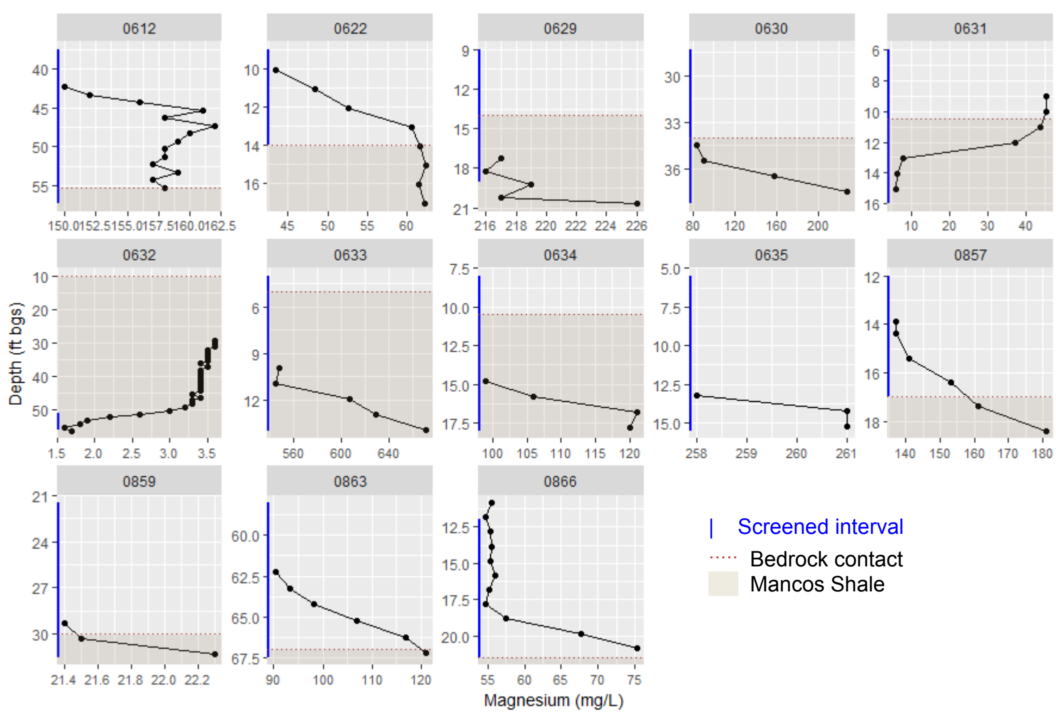

Figure C.1-8. Magnesium Profiles in Mill Tailings Area Wells

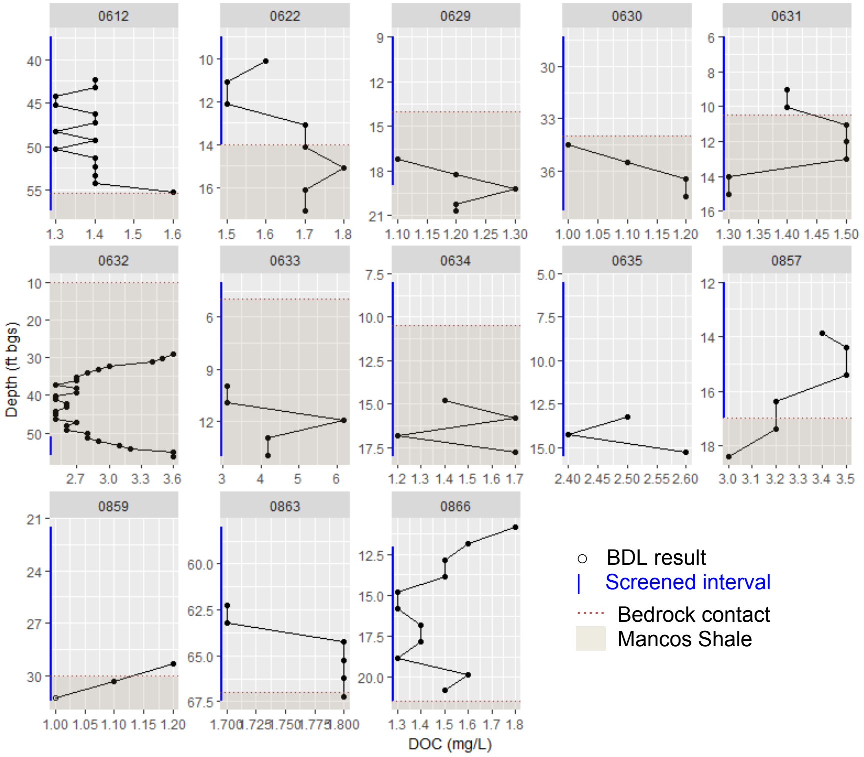

Figure C.1-9. DOC Profiles in Mill Tailings Area Wells

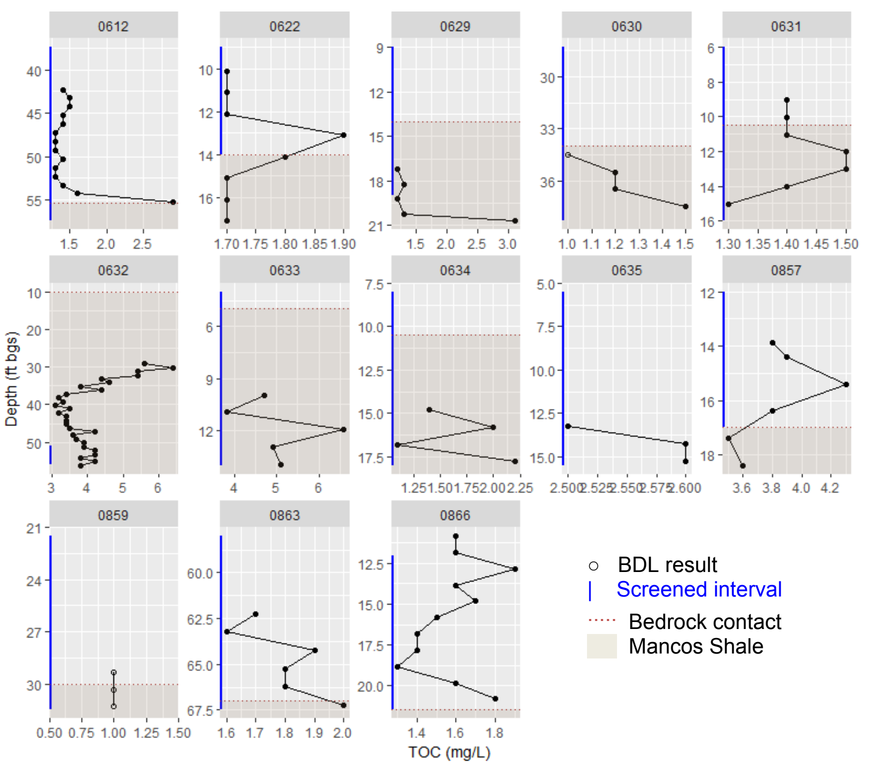

Figure C.1-10. TOC Profiles in Mill Tailings Area Wells

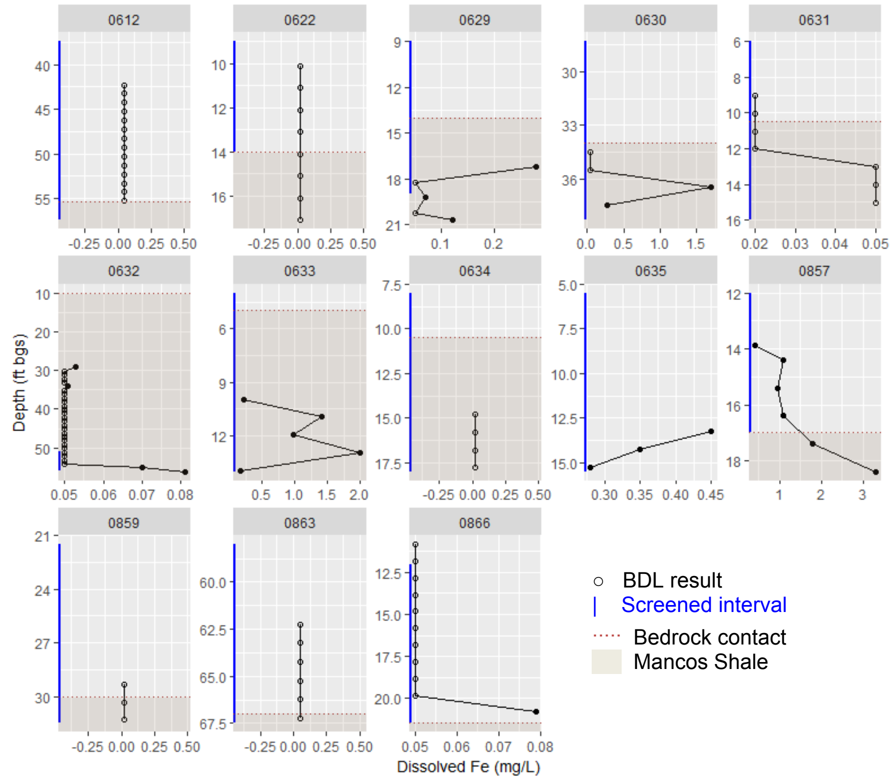

Figure C.1-11. Dissolved Iron Profiles in Mill Tailings Area Wells

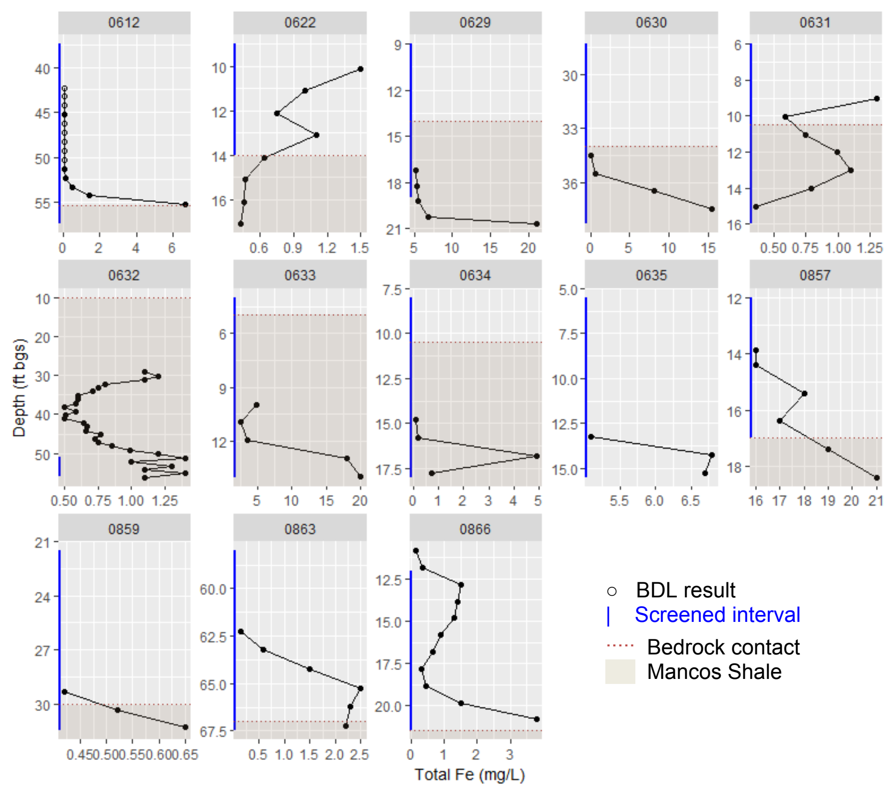

Figure C.1-12. Total Iron Profiles in Mill Tailings Area Wells

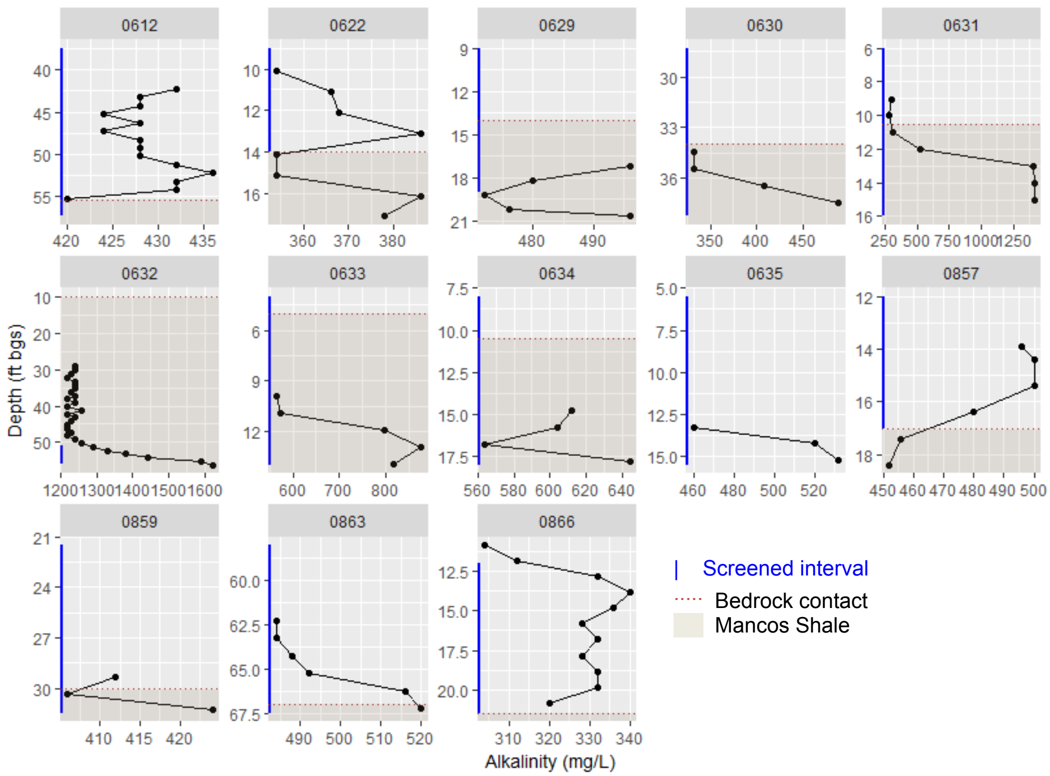

Figure C.1-13. Alkalinity (as $CaCO_3$) Profiles in Mill Tailings Area Wells

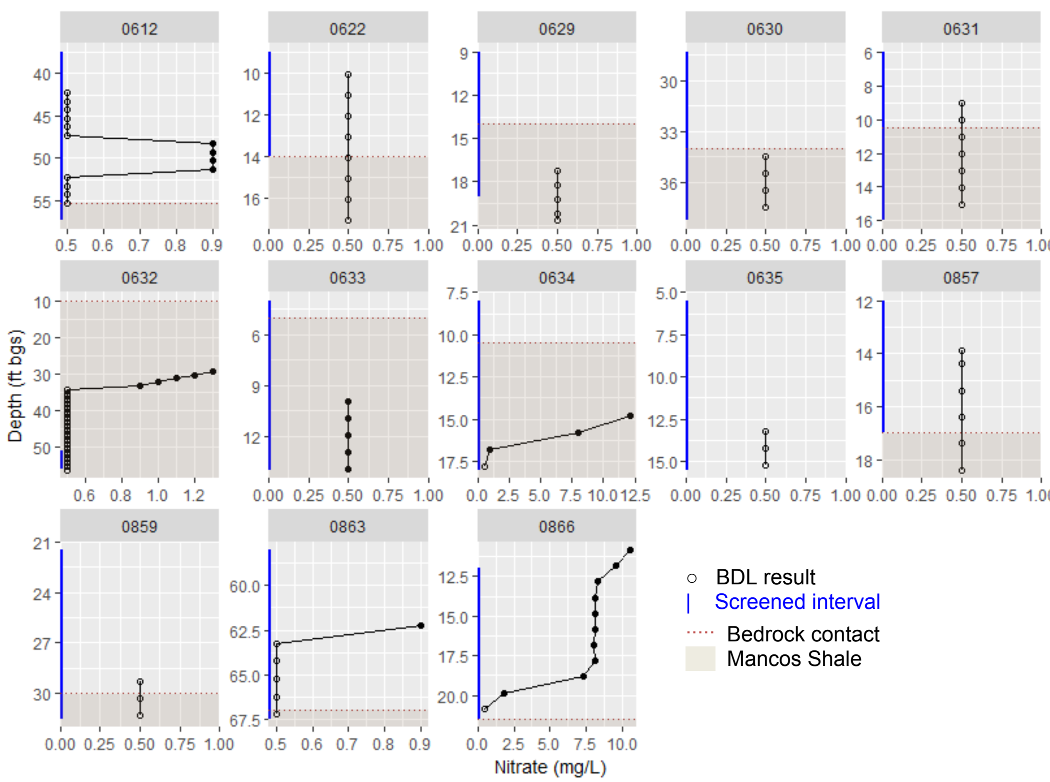

Figure C.1-14. Nitrate as NO_3 Profiles in Mill Tailings Area Wells

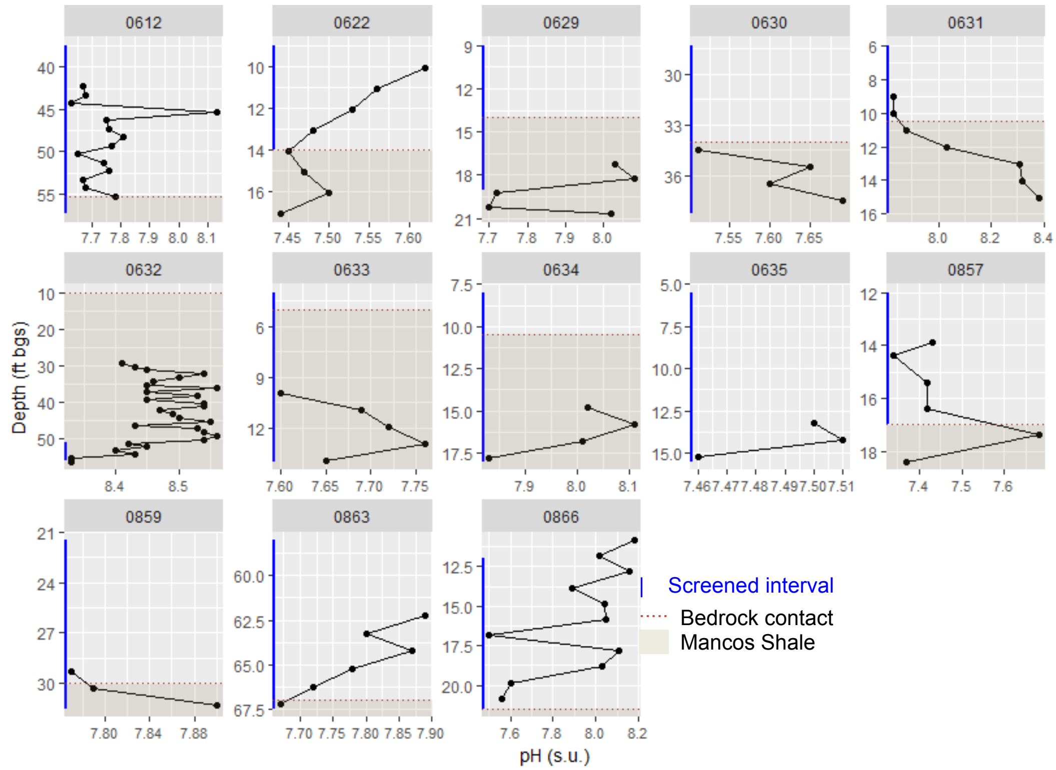

Figure C.1-15. pH Profiles in Mill Tailings Area Wells

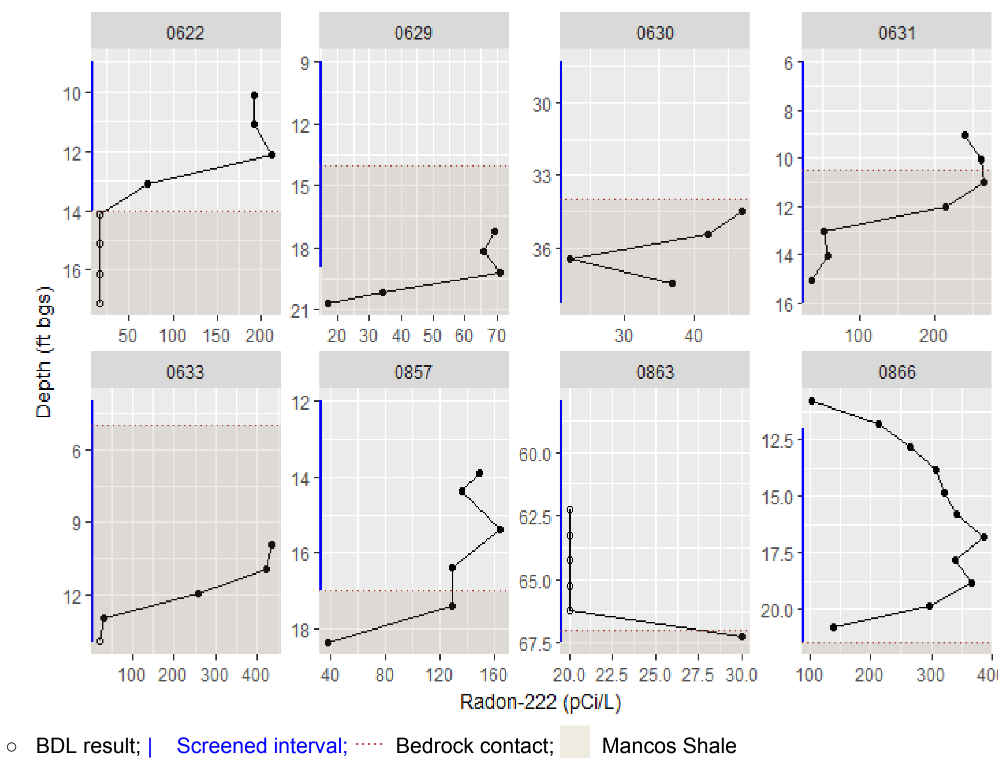

Figure C.1-16. Radon-222 Profiles in Mill Tailings Area Wells

Appendix C-2

Vertical Profiles by Well

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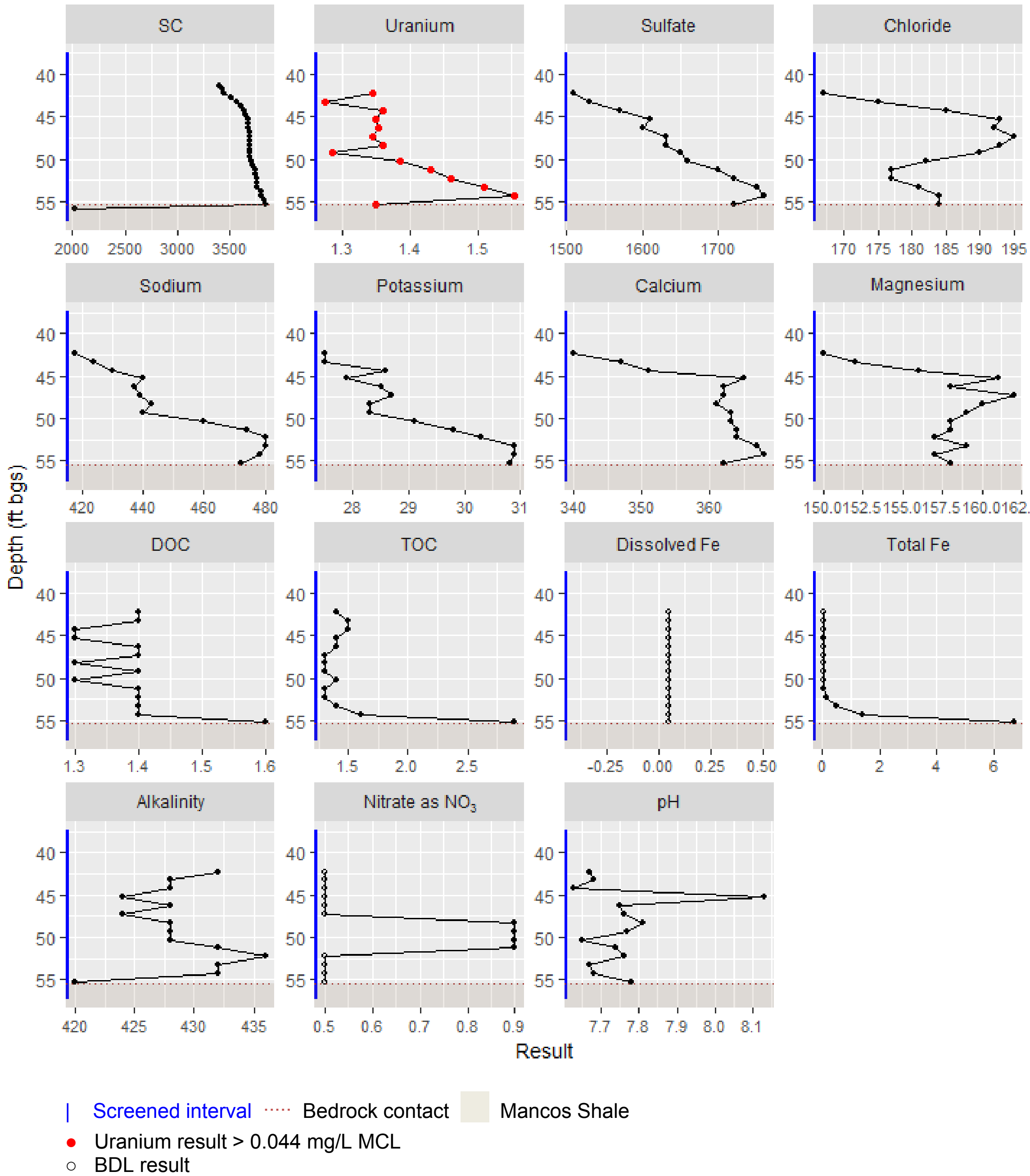
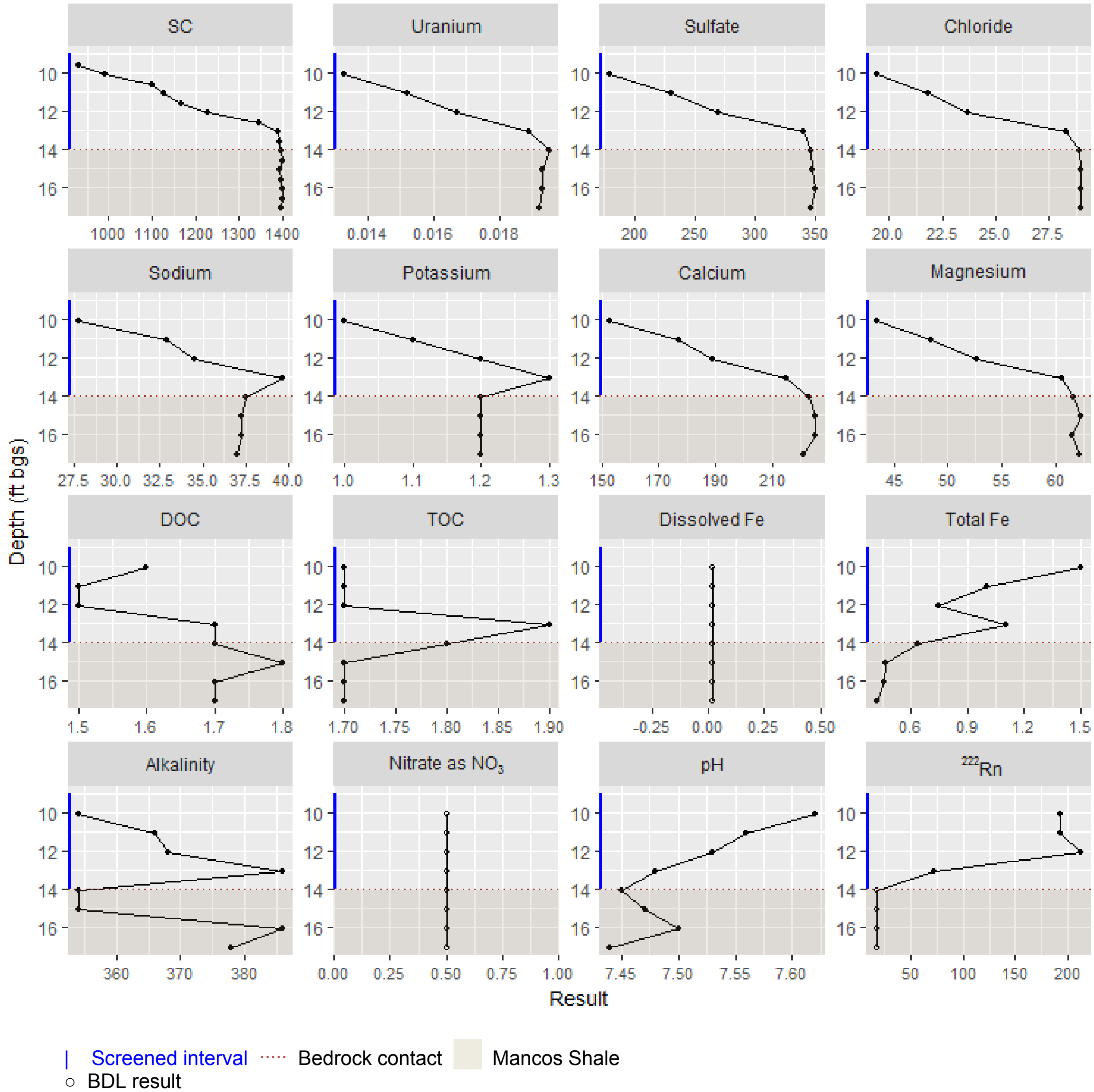


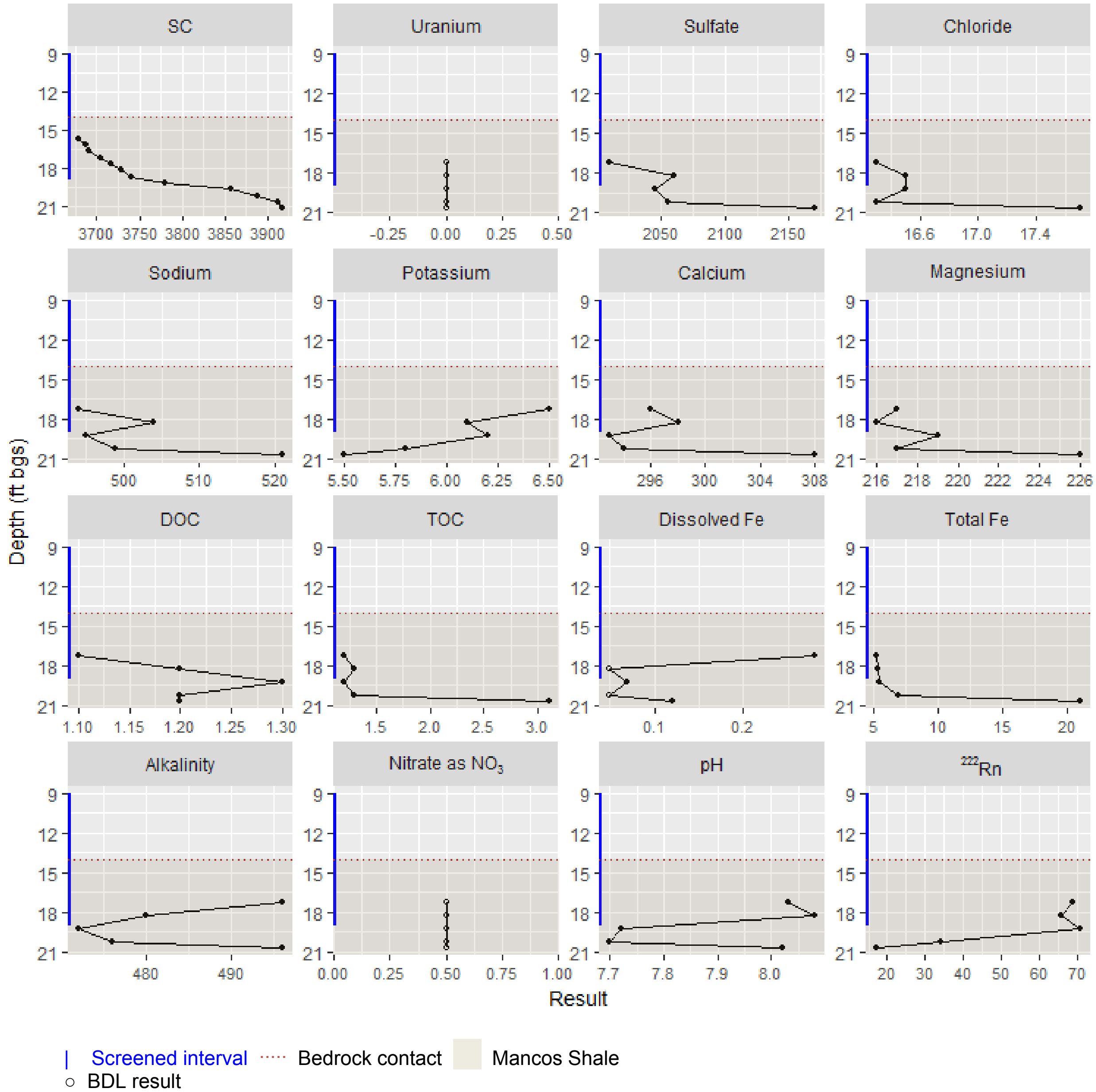
Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.
No nitrate results exceed the corresponding 40 CFR 192 MCL of 44 mg/L nitrate as NO_3

Figure C.2-1. Variable Profiles from Mill Tailings Area Well 0612, August 2015



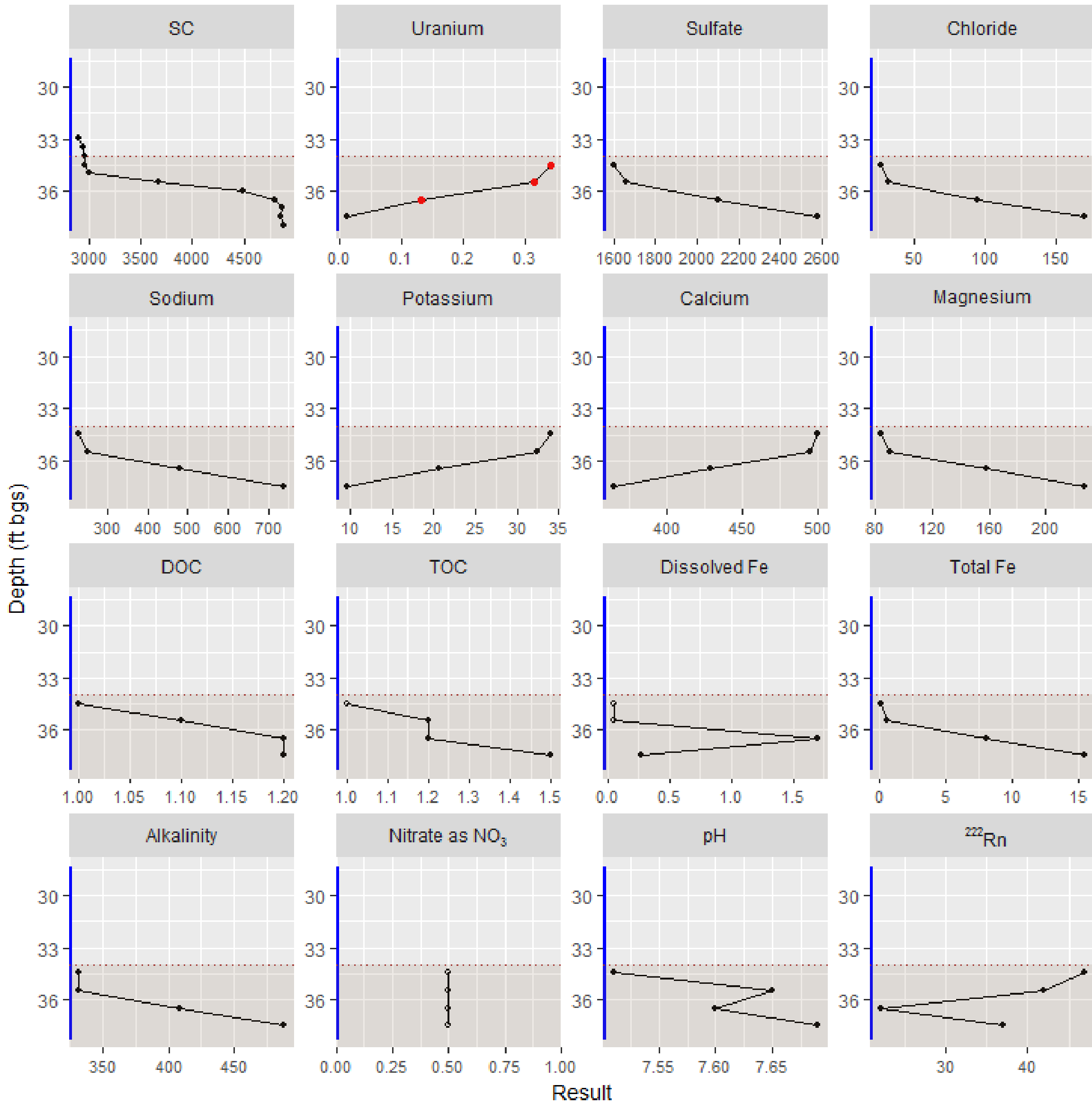
Notes:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

Figure C.2-2. Variable Profiles from Mill Tailings Area Background Well 0622, August–September 2015



Notes:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

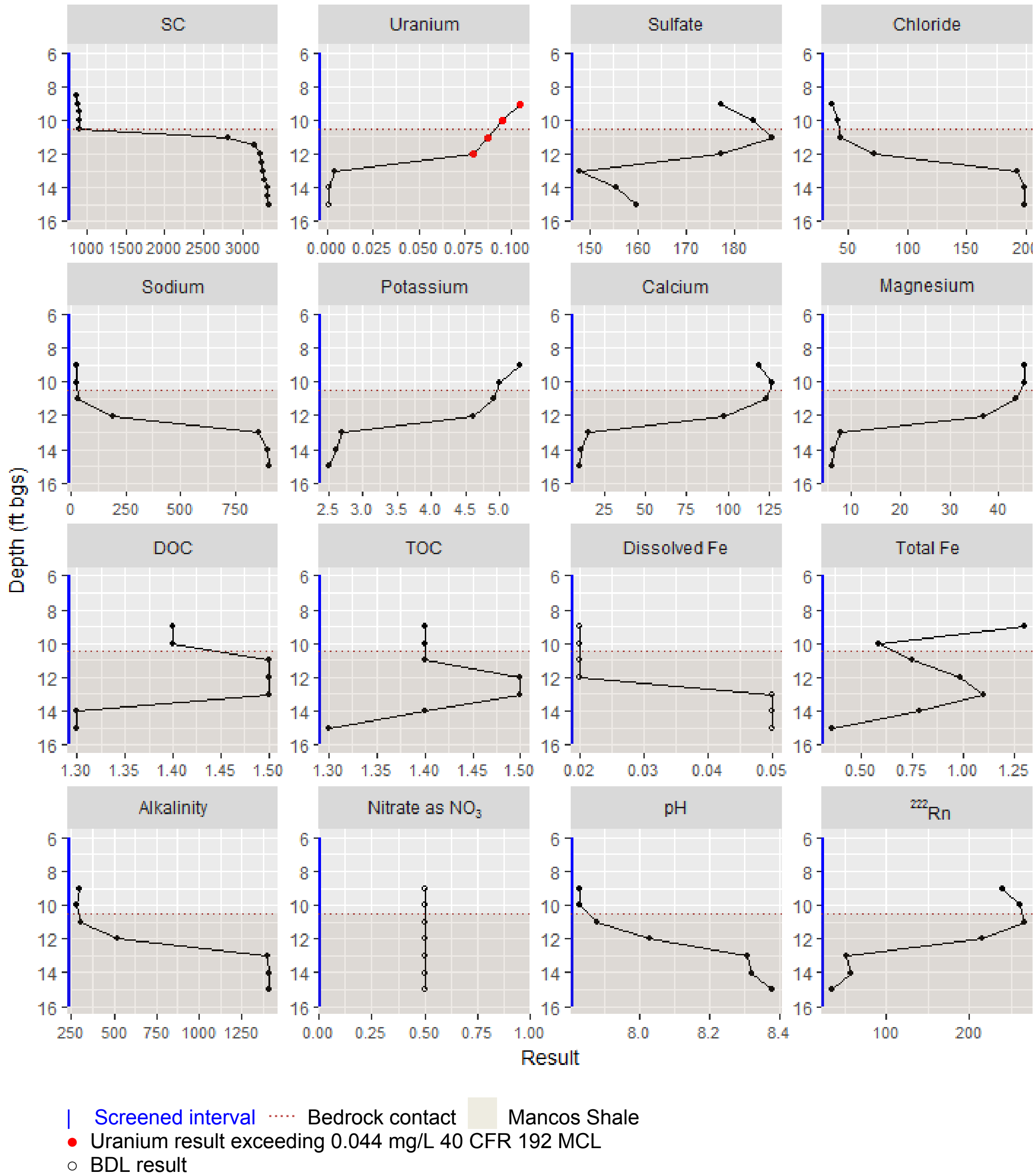
Figure C.2-3. Variable Profiles from Mill Tailings Area Background Well 0629, August–September 2015



| Screened interval ····· Bedrock contact Mancos Shale
○ BDL result
● Uranium result exceeding 0.044 mg/L 40 CFR 192 MCL

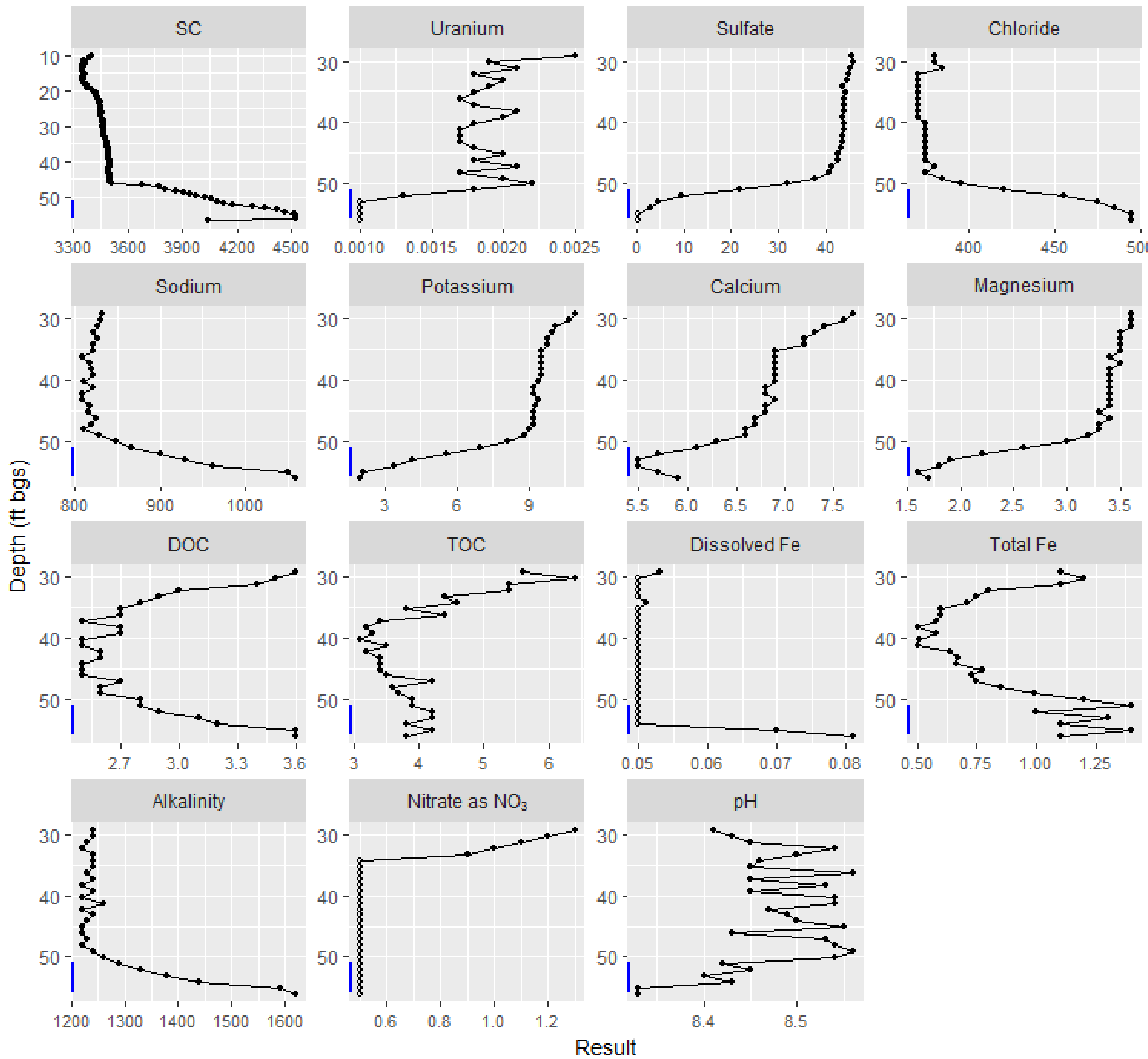
Notes:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$
No nitrate results exceed the corresponding 44 mg/L MCL

Figure C.2-4. Variable Profiles from Mill Tailings Area Well 0630, August 2015



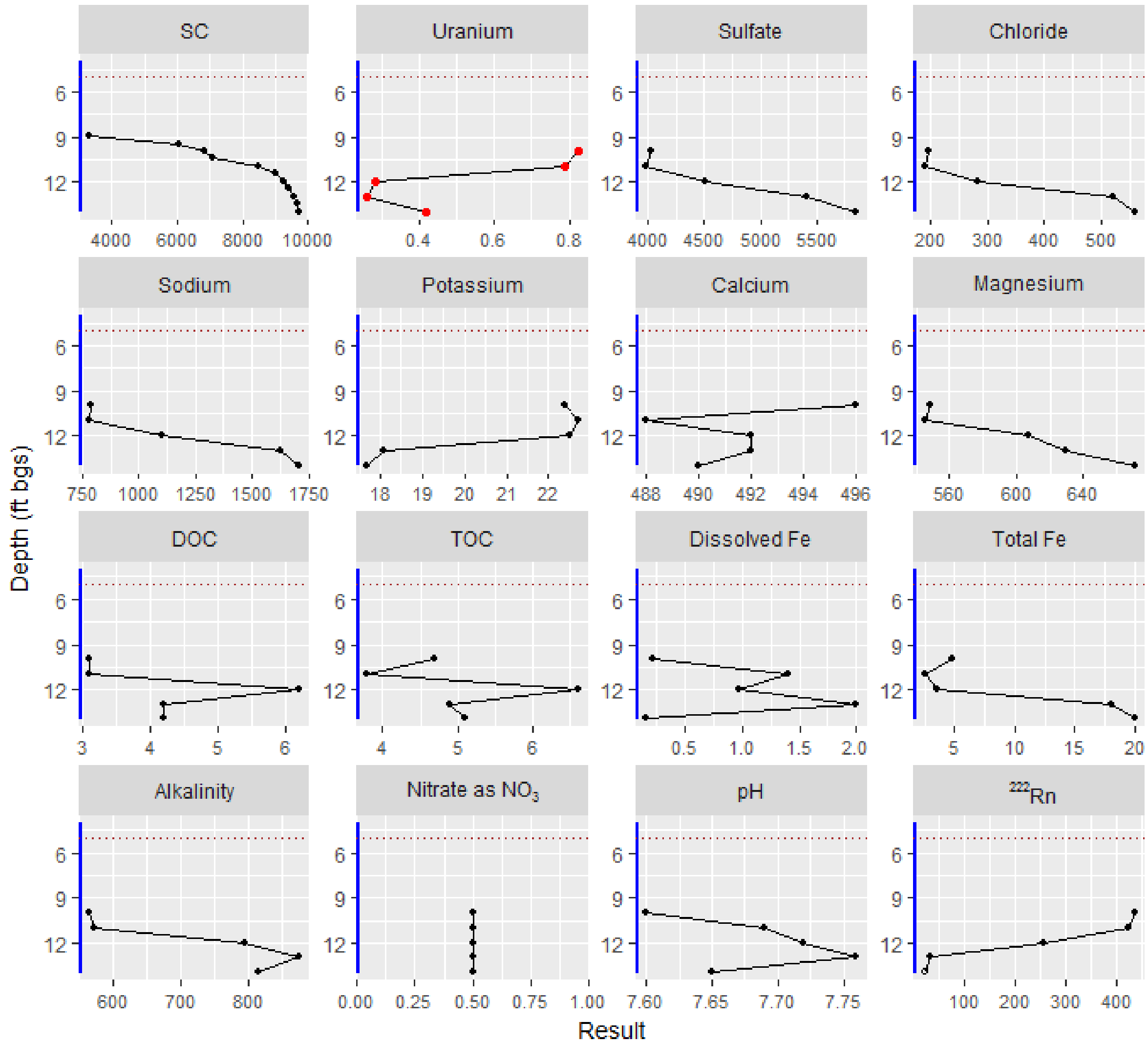
Notes:
All units in mg/L except SC (μS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$

Figure C.2-5. Variable Profiles from Mill Tailings Area Well 0631, August 2015



Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

Figure C.2-6. Variable Profiles from Mill Tailings Area Mancos Shale Well 0632, September 2015



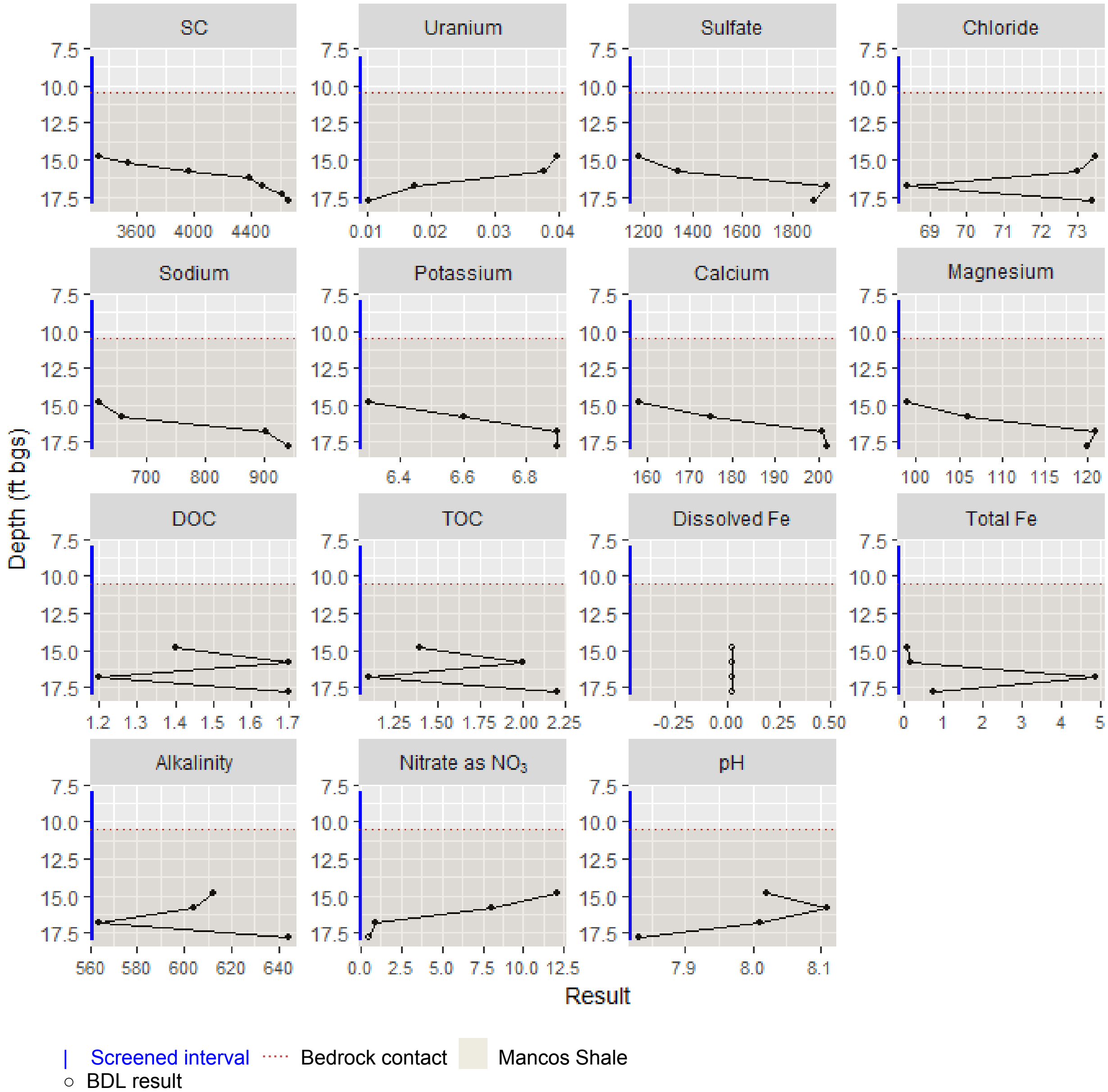
| Screened interval ····· Bedrock (Mancos Shale) contact

● Result exceeding corresponding 40 CFR 192 MCL: 0.044 mg/L uranium and 44 mg/L nitrate as NO_3

○ BDL result

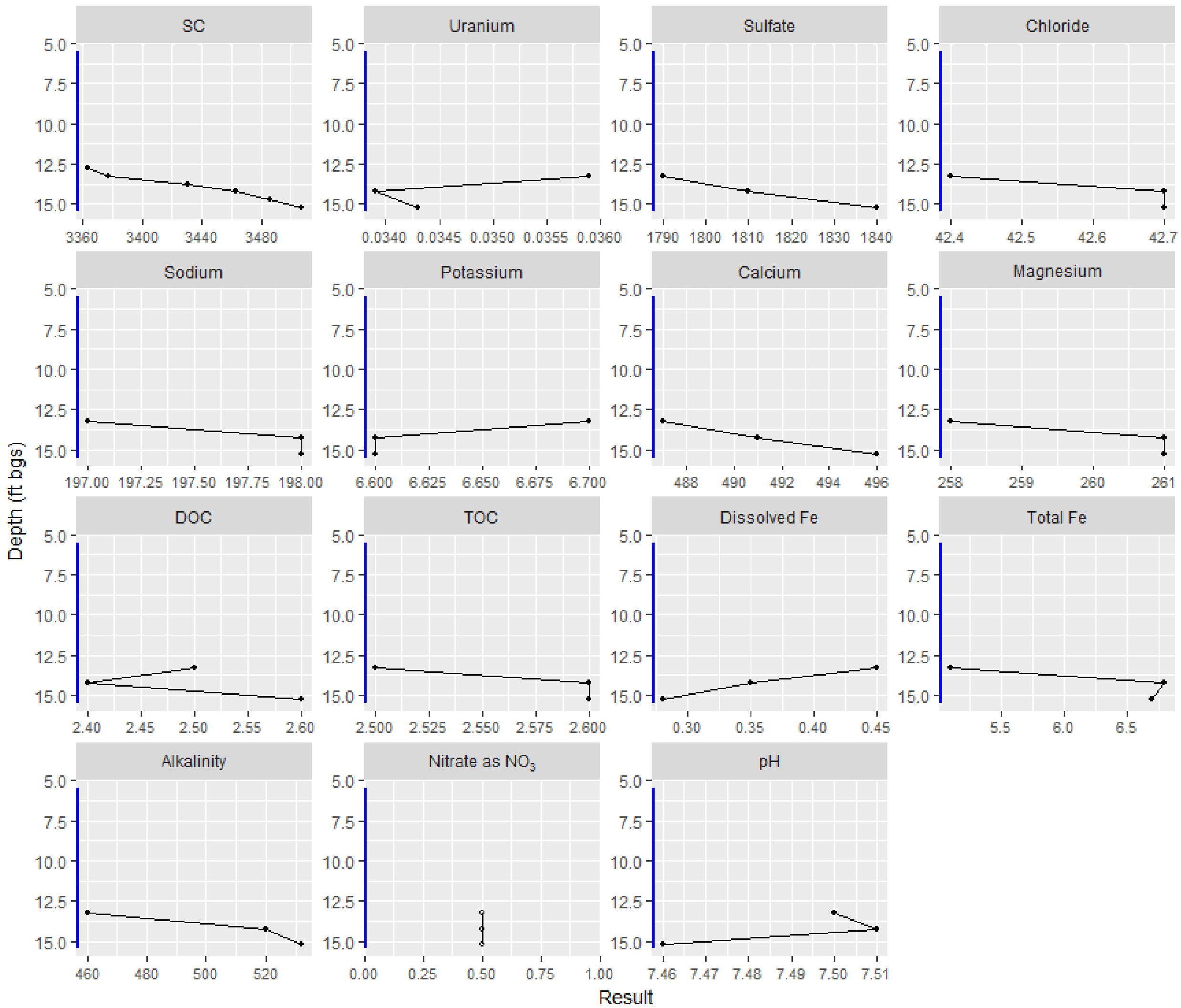
Note:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$

Figure C.2-7. Variable Profiles from Mill Tailings Area Well 0633, August 2015



Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

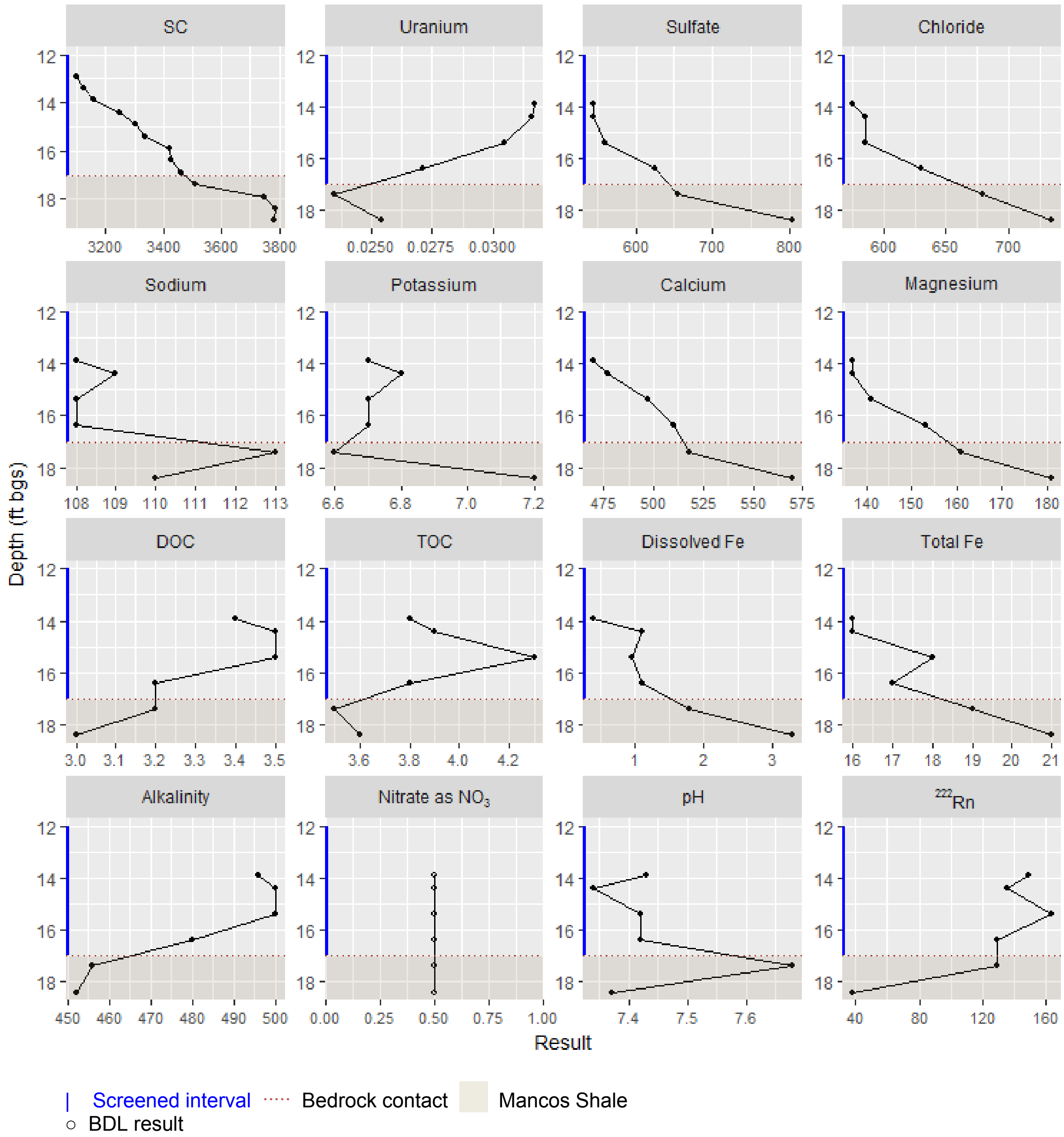
Figure C.2-8. Variable Profiles from Mill Tailings Area Well 0634, August 2015



| Screened interval
○ BDL result

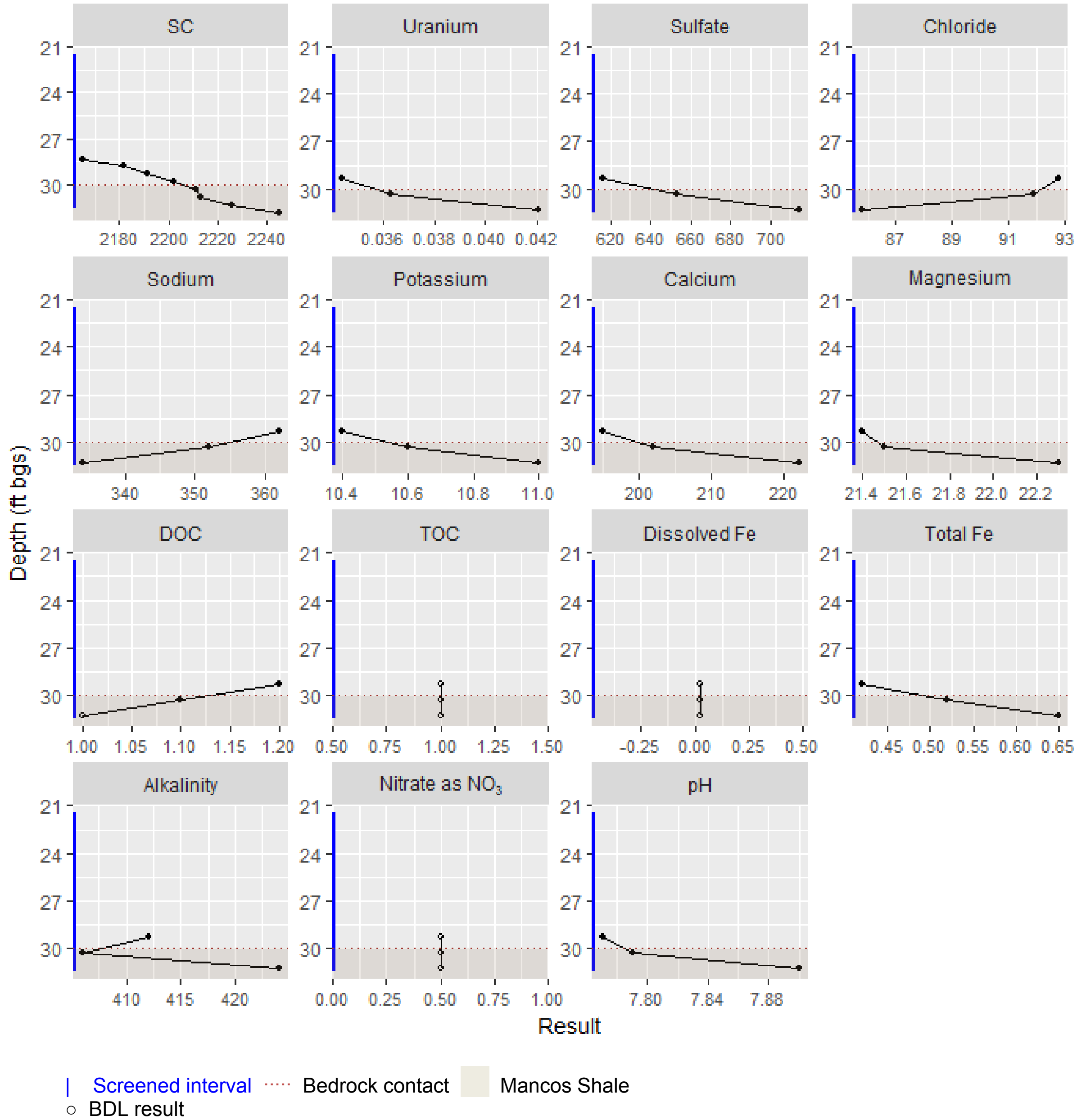
Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

Figure C.2-9. Variable Profiles from Mill Tailings Area Alluvial Well 0635, August 2015



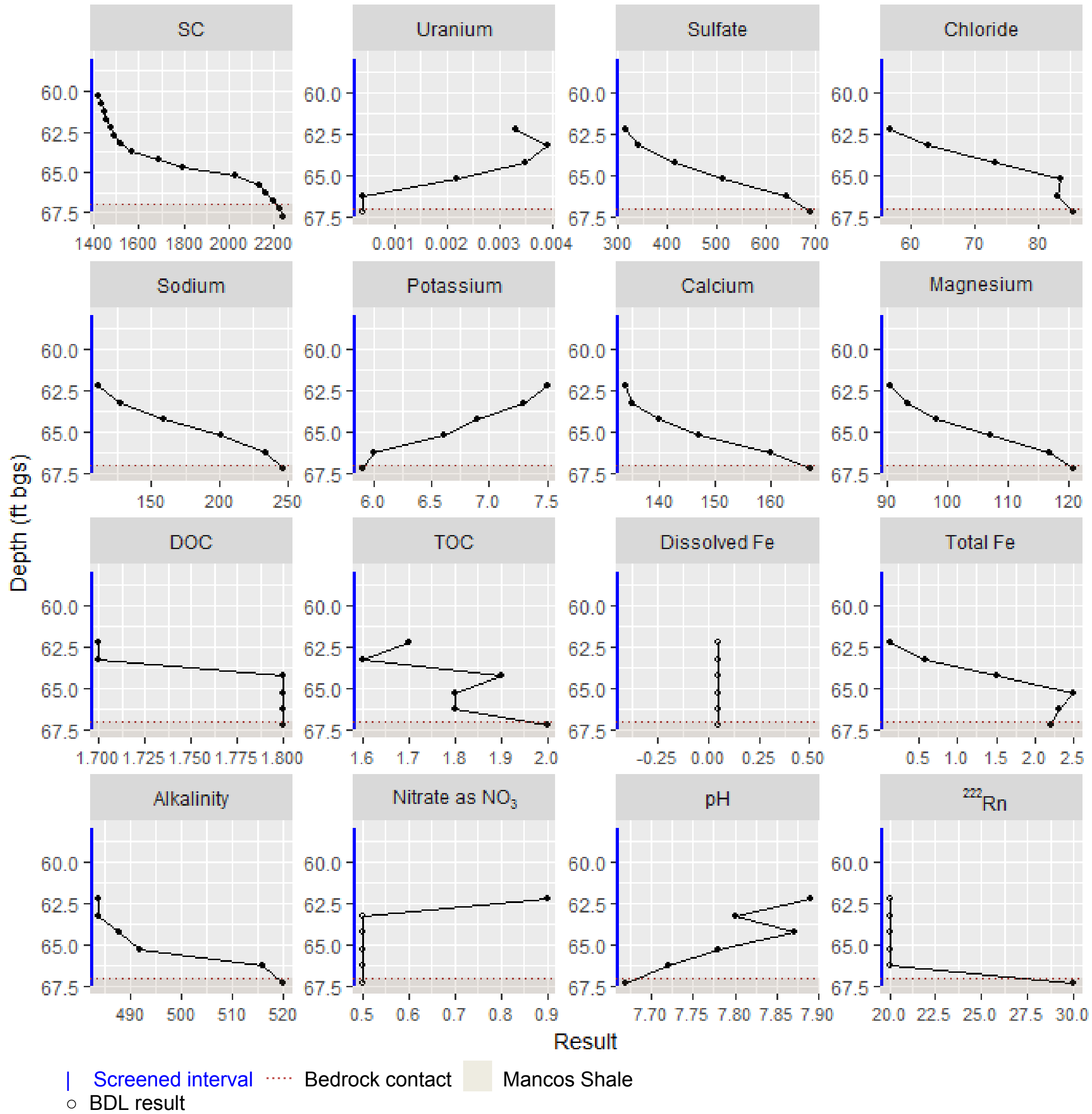
Notes:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

Figure C.2-10. Variable Profiles from Mill Tailings Area Background Well 0857, August–September 2015



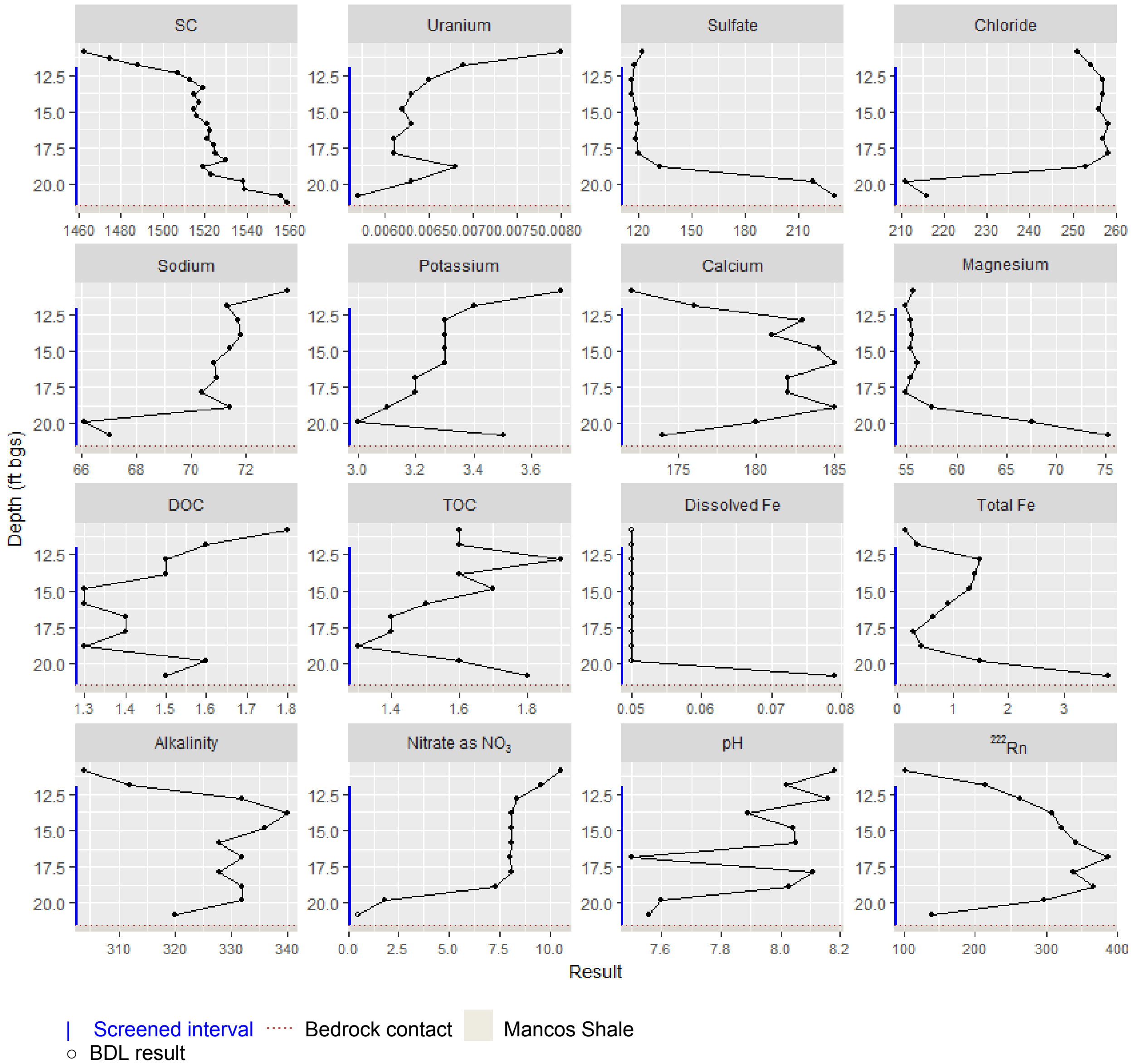
Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

Figure C.2-11. Variable Profiles from Mill Tailings Area Well 0859, August 2015



Notes:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

Figure C.2-12. Variable Profiles from Mill Tailings Area Well 0863, August–September 2015



Notes:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$
For uranium and nitrate, no results exceed the corresponding 40 CFR 192 MCL:
0.044 mg/L uranium and 44 mg/L nitrate as NO_3

Figure C.2-13. Variable Profiles from Mill Tailings Area Background Well 0866, August–September 2015

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Appendix D

Durango Processing Site Raffinate Ponds Area SC and Analyte Profiles

Preface

Phase II of this study yielded 168 analyte profiles for former raffinate ponds area wells (11 wells × 15 parameters + 3 ^{222}Rn profiles). The discussion in the main body of the report focused mainly on SC, uranium, sulfate, and ^{222}Rn and on those wells with the most variable or interesting profiles. This appendix provides a comprehensive graphical summary of Phase II results for all raffinate ponds area well-variable combinations.

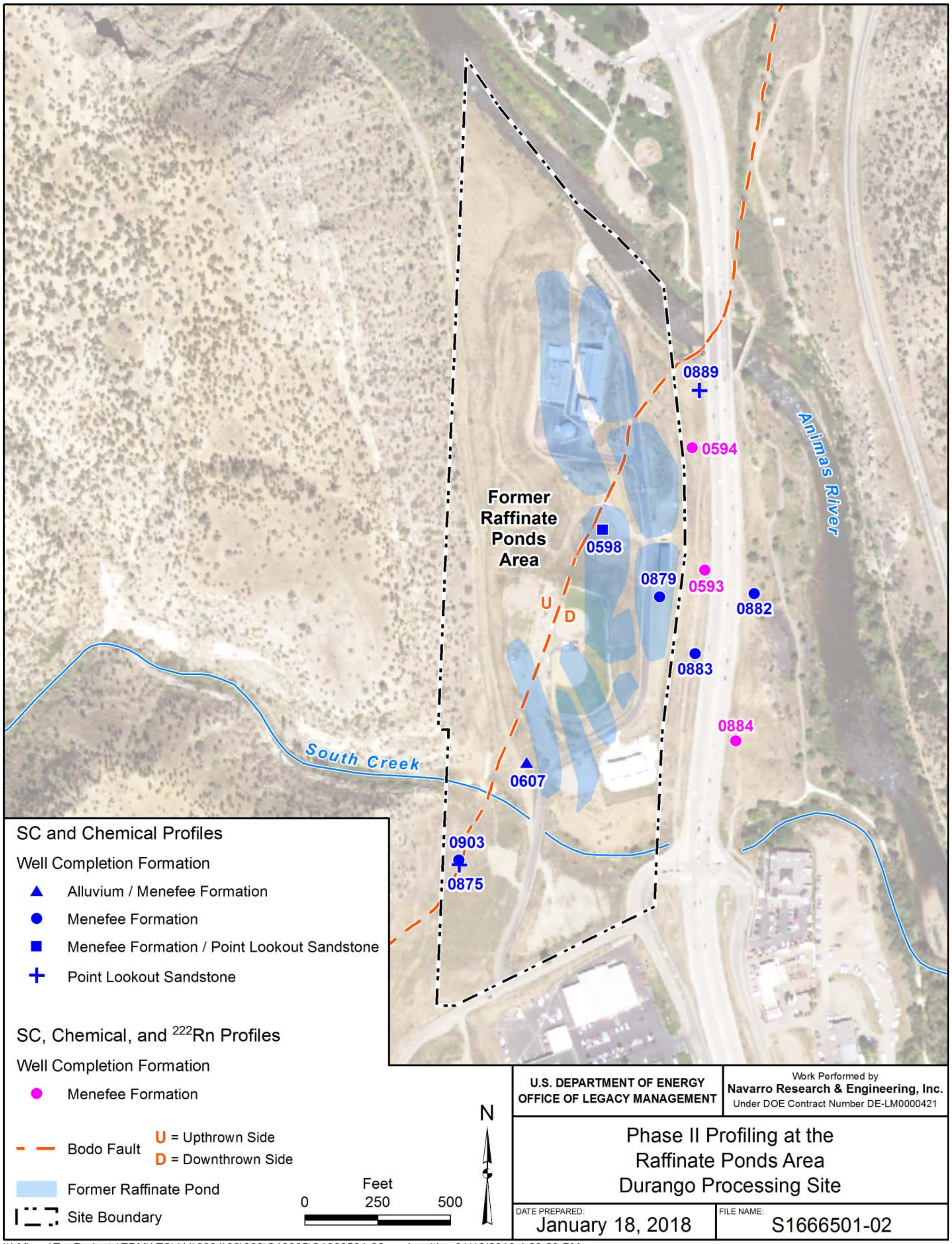
Appendix D-1 plots the profiles by variable, by well. For a given analyte, this presentation allows comparison of profiles between wells. Appendix D-2 provides a different view, plotting profiles of all parameters for each well. When interpreting these figures, it is important to acknowledge the range in values because scales are unique for each well- and variable-specific profile. As such, some profiles initially appearing as being highly variable may just represent random variation if the range of measurements is small. Because this appendix is intended as a stand-alone summary of all Phase II results, some figures from the main body of the report are duplicated. Legend items and abbreviations used globally are listed below.

Legend Items:

|	Screened interval
·····	Bedrock (MF) contact
*	Routinely sampled well
○	BDL result

Abbreviations:

AL	alluvium
BDL	below detection limit (denoted by ○ in plots)
bgs	below ground surface
DOC	dissolved organic carbon
Fe	iron
MCL	maximum concentration limit established in 40 CFR 192
mg/L	milligrams per liter
MF	Menefee Formation
μS/cm	microsiemens per centimeter
PL	Point Lookout Sandstone
SC	specific conductance
TOC	total organic carbon



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Note: Figure duplicated from Figure 24 of the main text.

Durango Processing Site Raffinate Ponds Area Wells Profiled in Phase II

Appendix D-1

Vertical Profiles by Analyte

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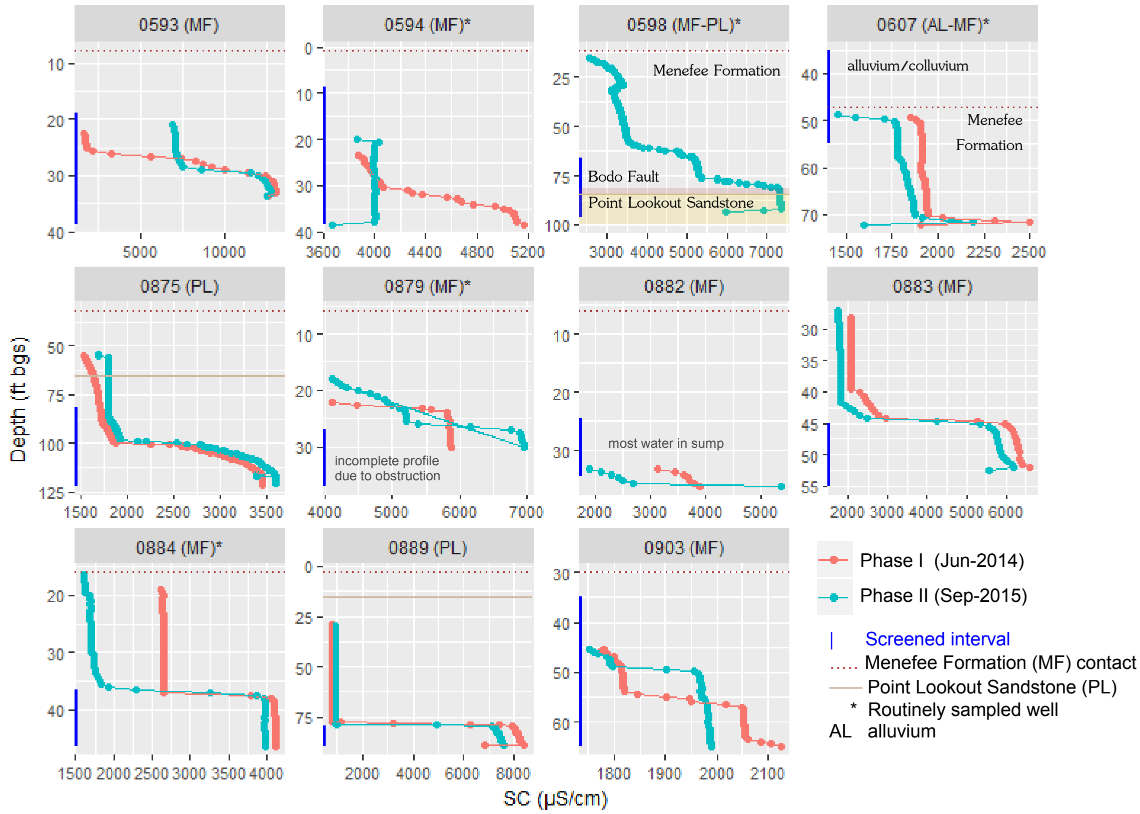

Figure D.1-1. Specific Conductance Profiles in Raffinate Ponds Area Wells

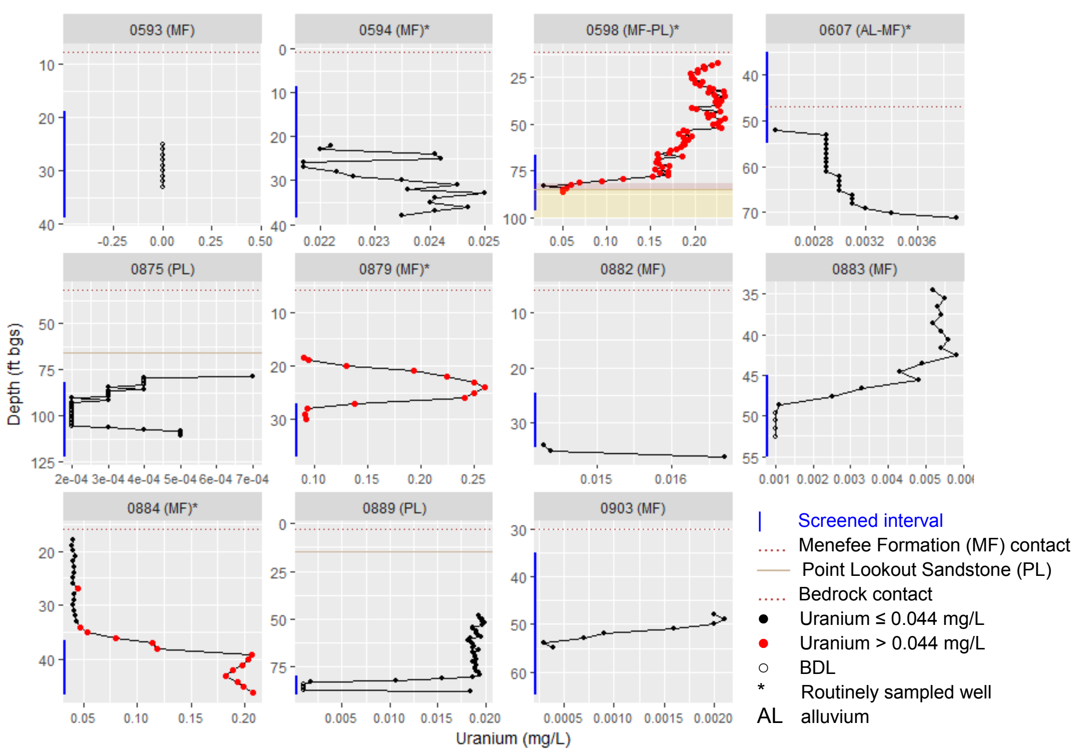

Figure D.1-2. Uranium Profiles in Raffinate Ponds Area Wells

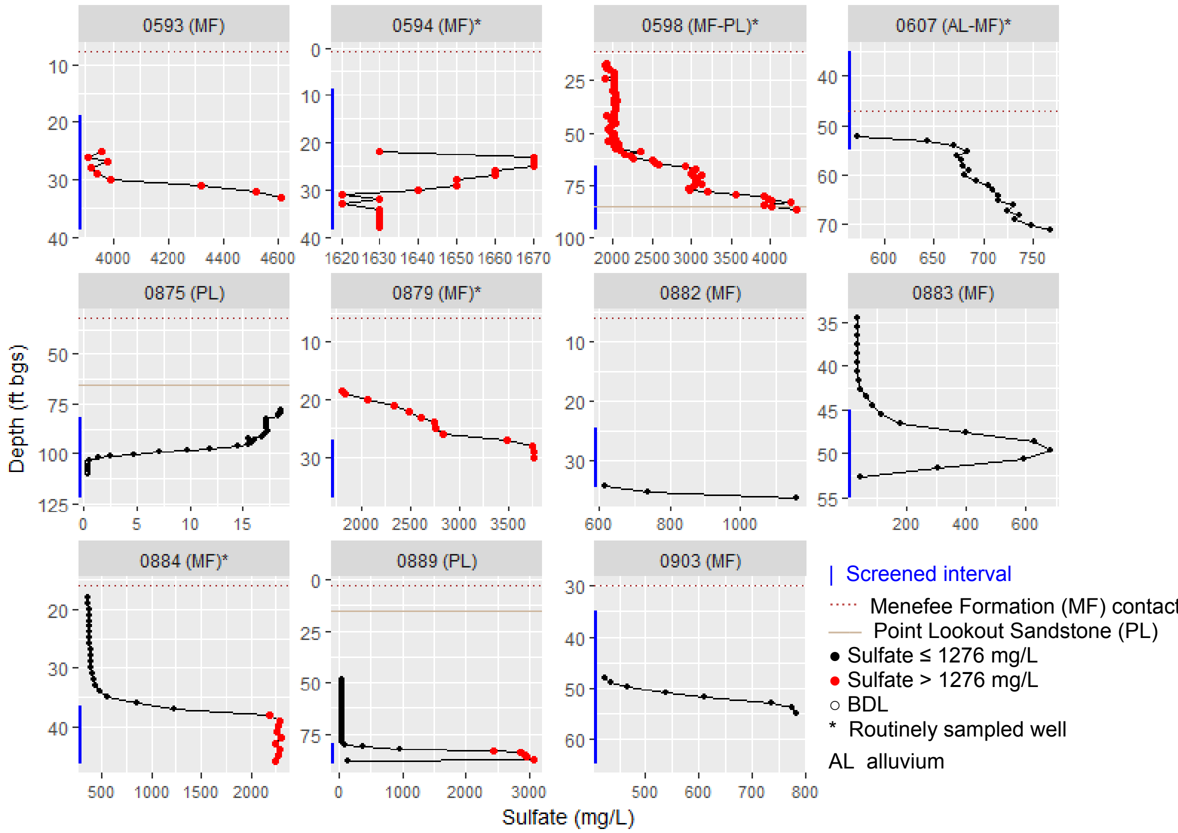

Figure D.1-3. Sulfate Profiles in Raffinate Ponds Area Wells

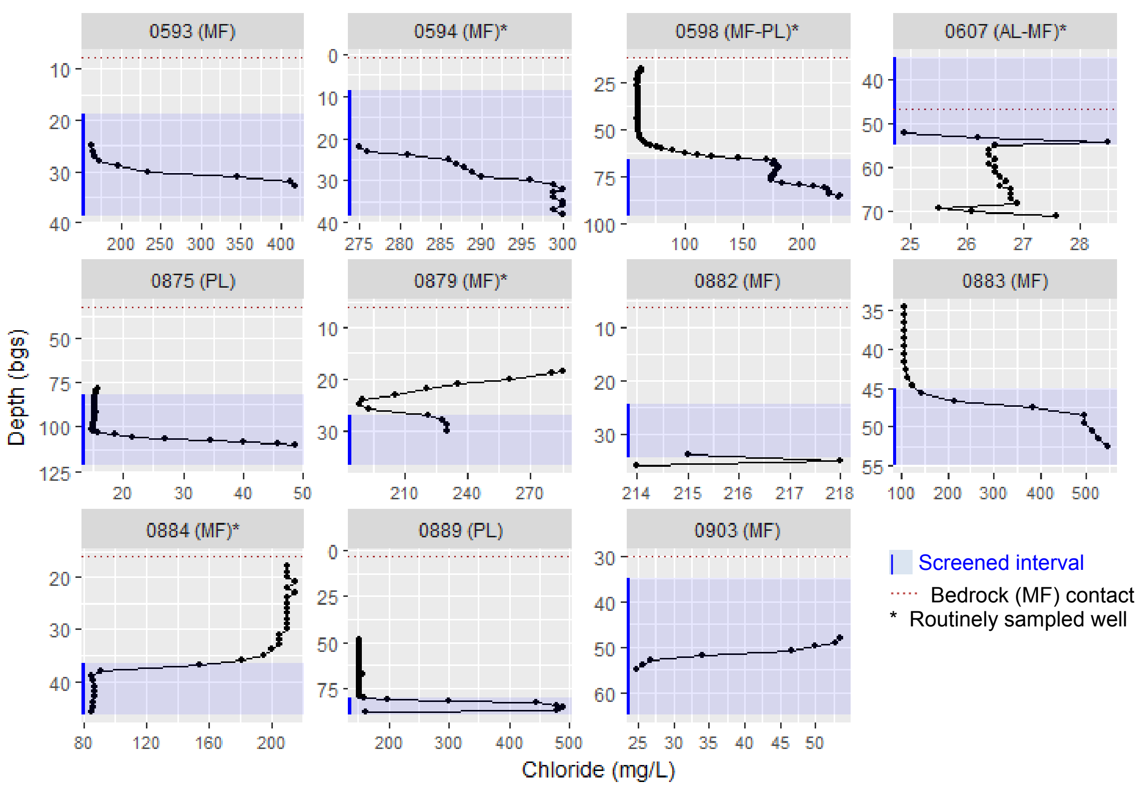

Figure D.1-4. Chloride Profiles in Raffinate Ponds Area Wells

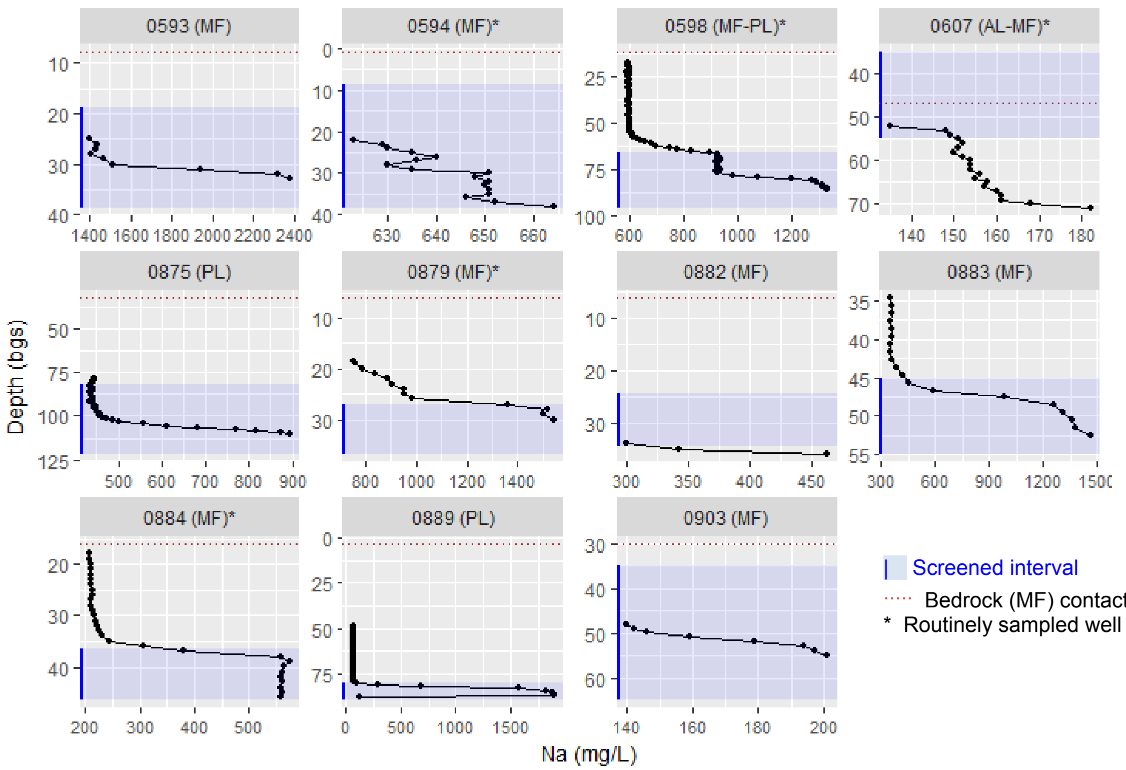

Figure D.1-5. Sodium Profiles in Raffinate Ponds Area Wells

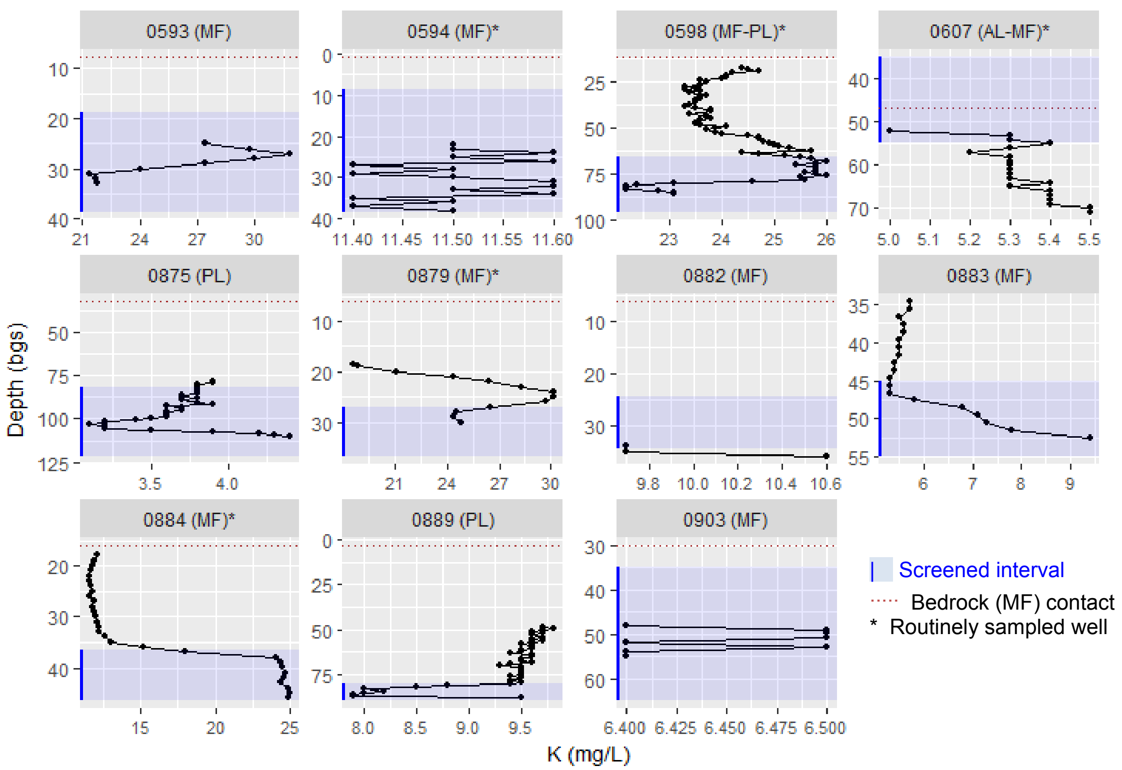

Figure D.1-6. Potassium Profiles in Raffinate Ponds Area Wells

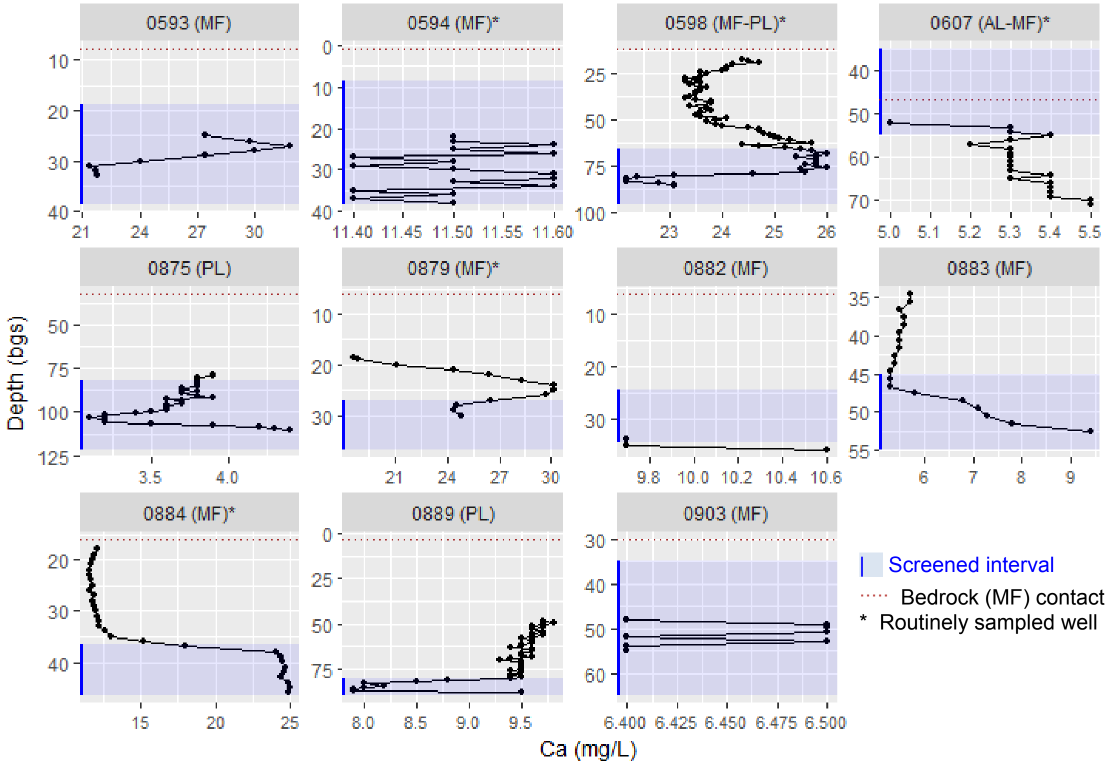

Figure D.1-7. Calcium Profiles in Raffinate Ponds Area Wells

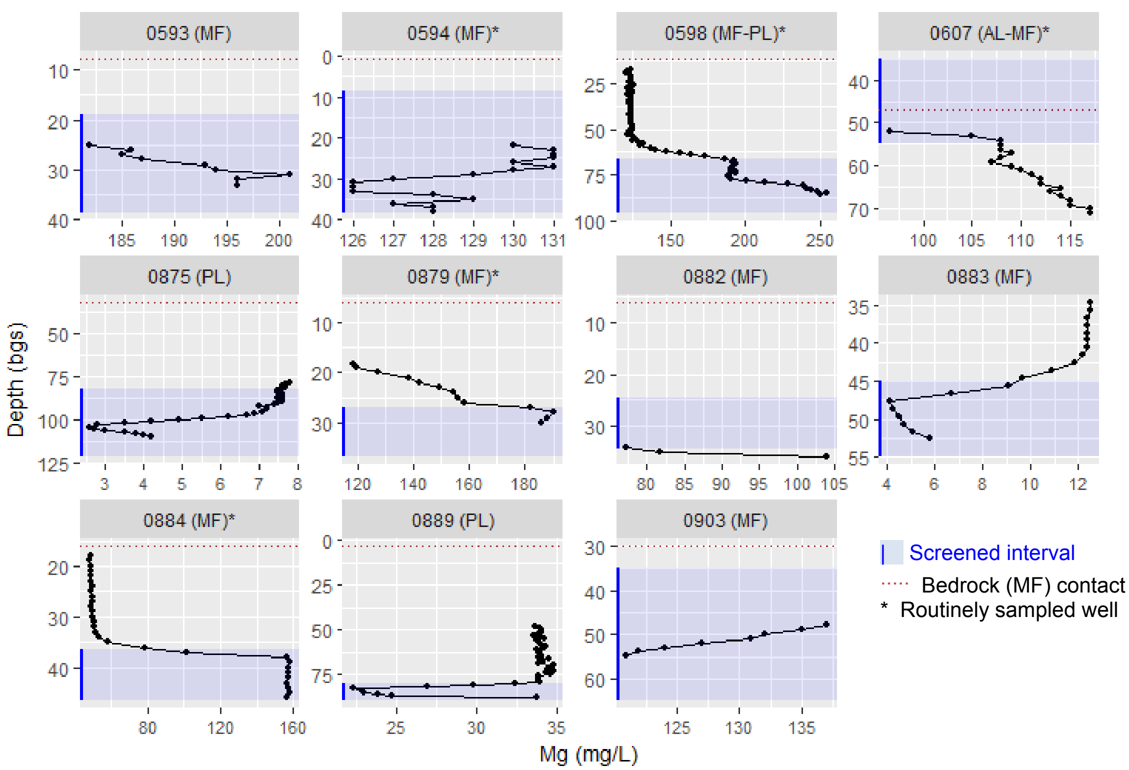

Figure D.1-8. Magnesium Profiles in Raffinate Ponds Area Wells

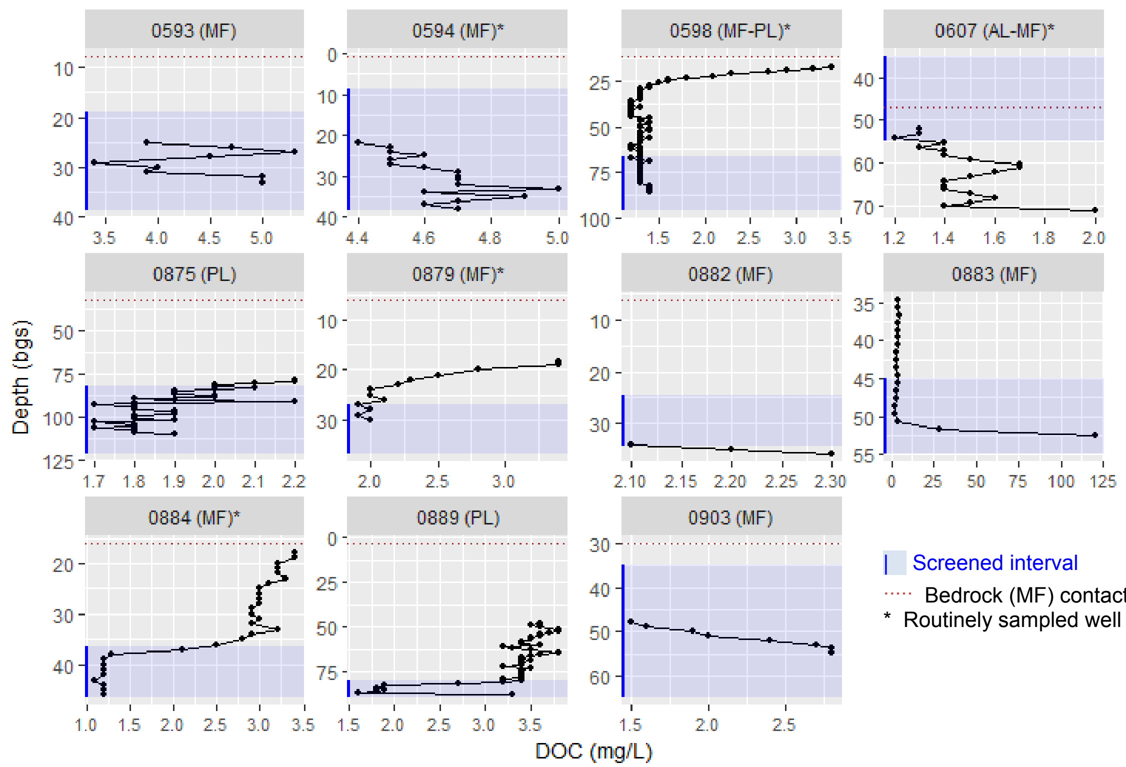

Figure D.1-9. DOC Profiles in Raffinate Ponds Area Wells

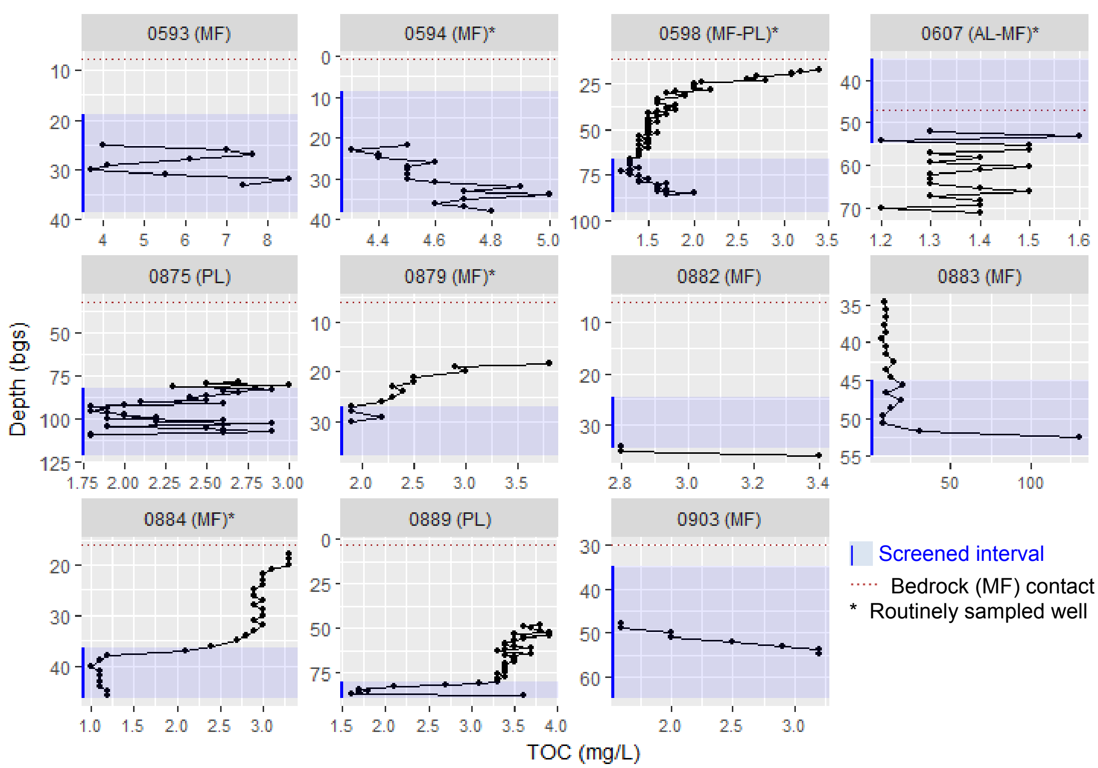

Figure D.1-10. TOC Profiles in Raffinate Ponds Area Wells

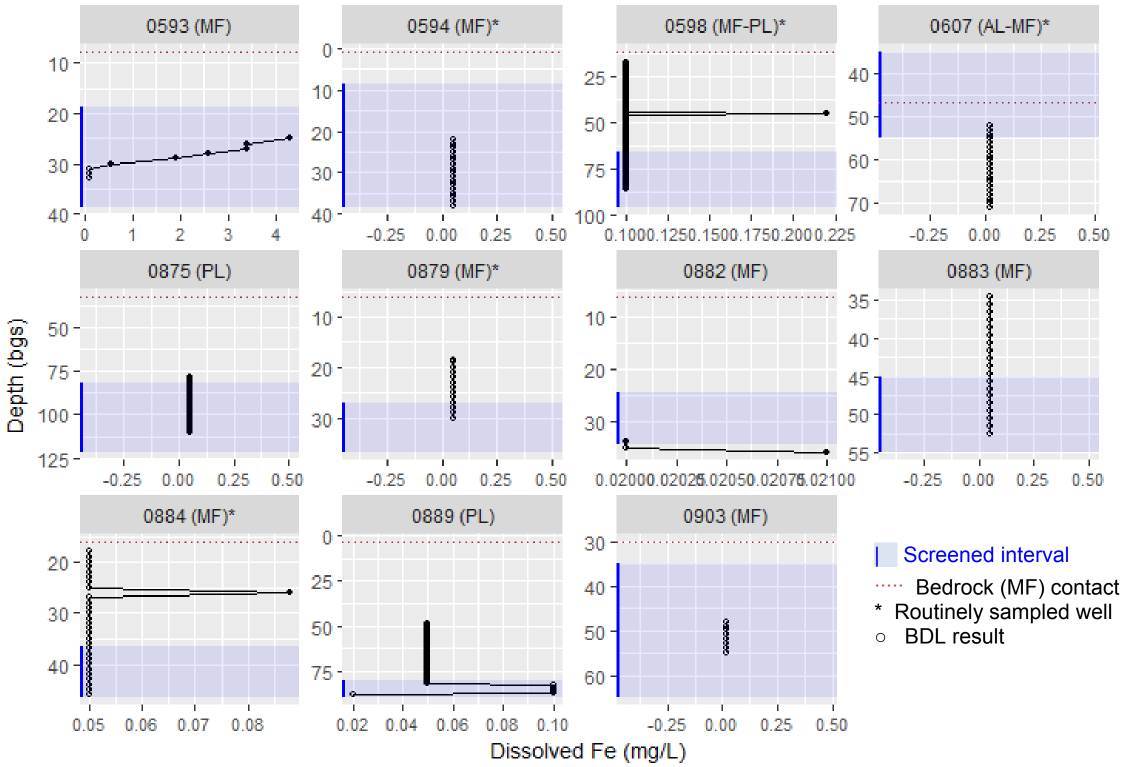

Figure D.1-11. Dissolved Iron Profiles in Raffinate Ponds Area Wells

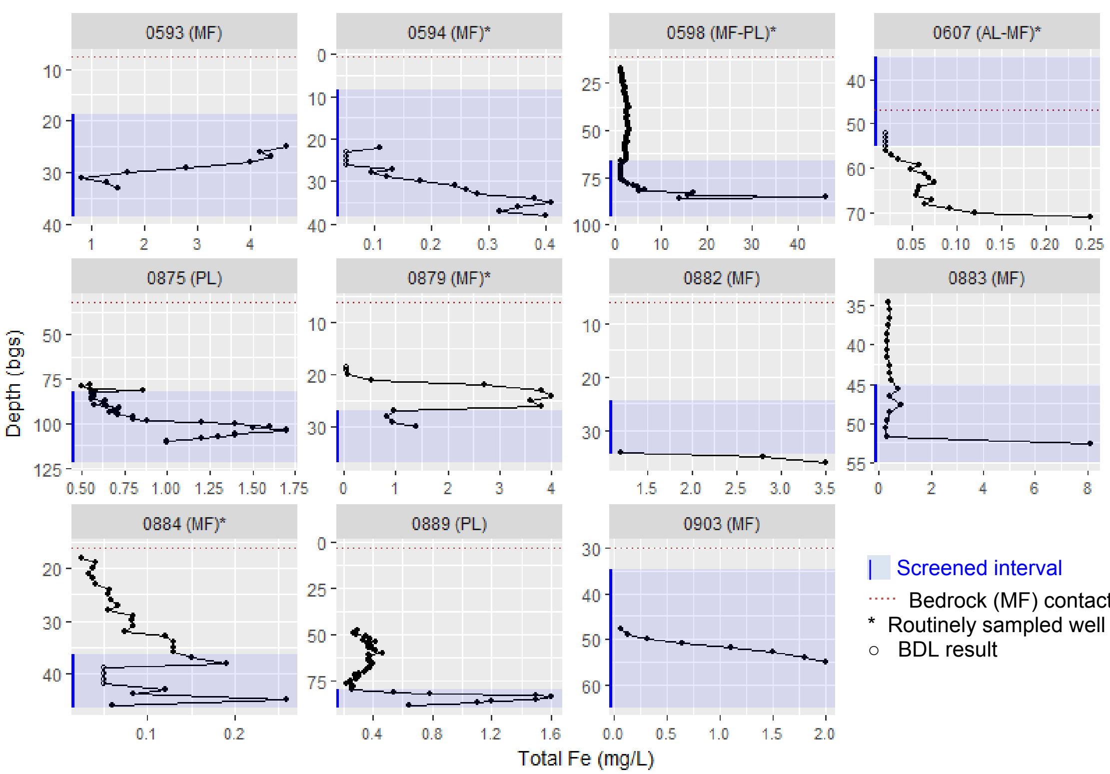

Figure D.1-12. Total Iron Profiles in Raffinate Ponds Area Wells

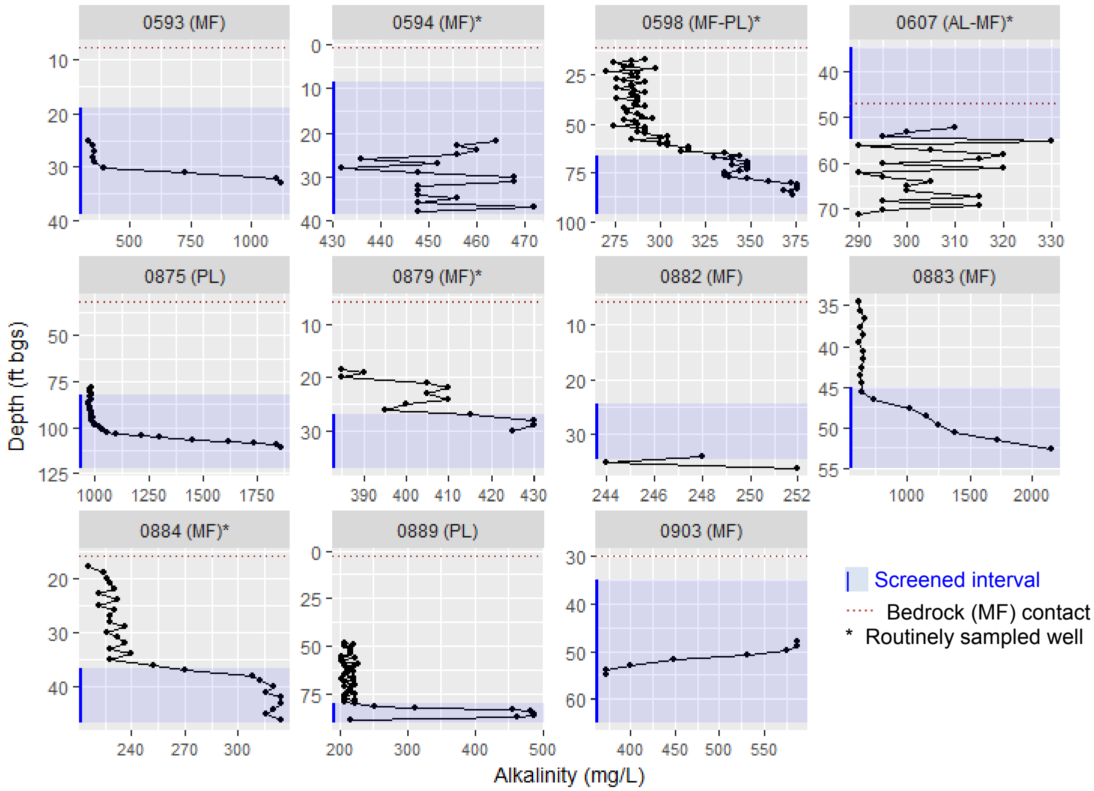

Figure D.1-13. Alkalinity (as $CaCO_3$) Profiles in Raffinate Ponds Area Wells

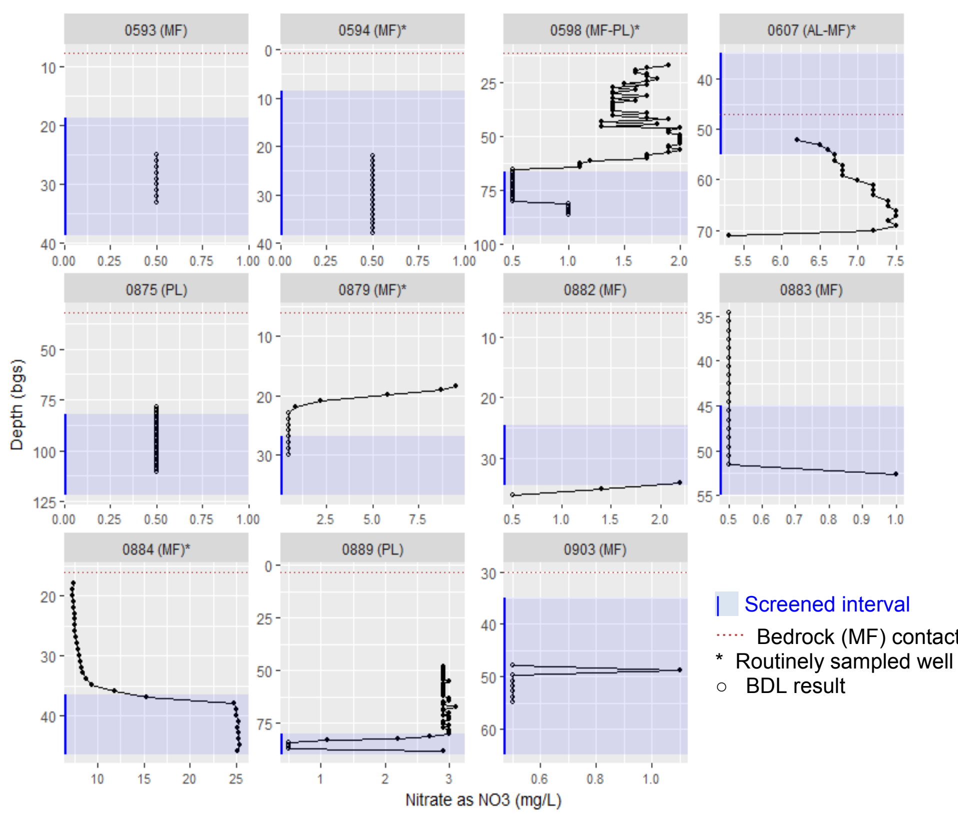

Figure D.1-14. Nitrate as NO_3 Profiles in Raffinate Ponds Area Wells

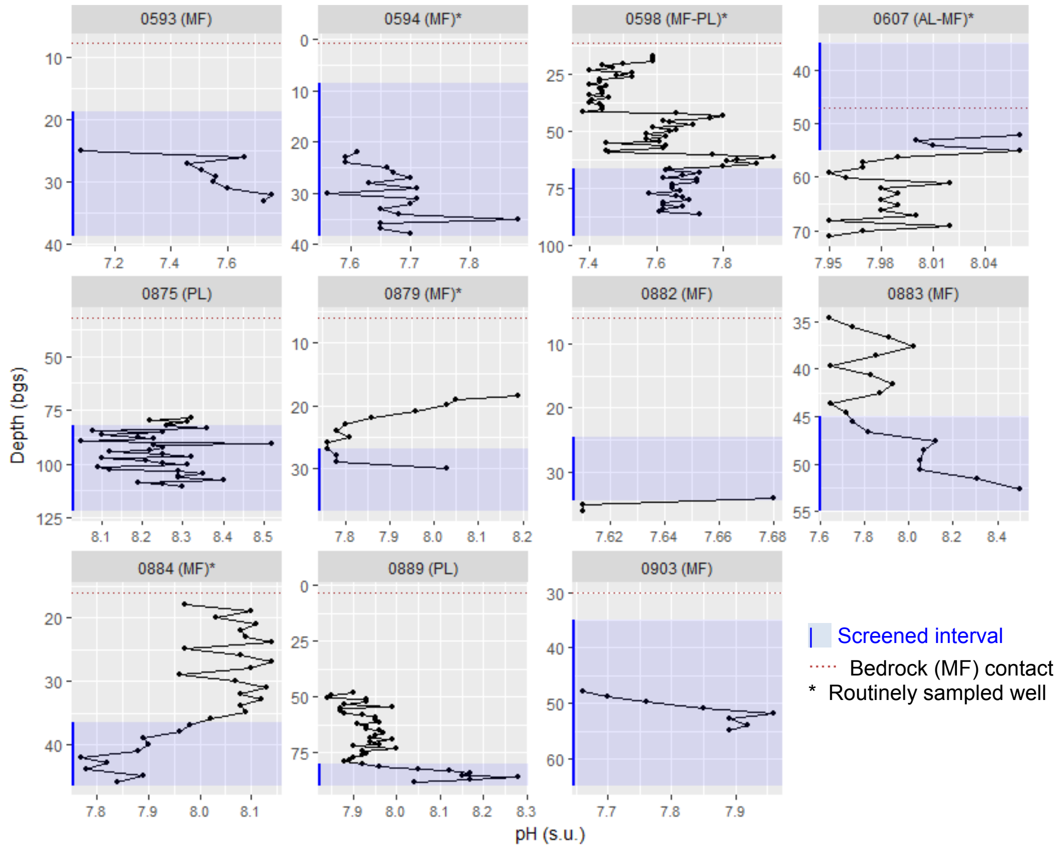

Figure D.1-15. pH Profiles in Raffinate Ponds Area Wells

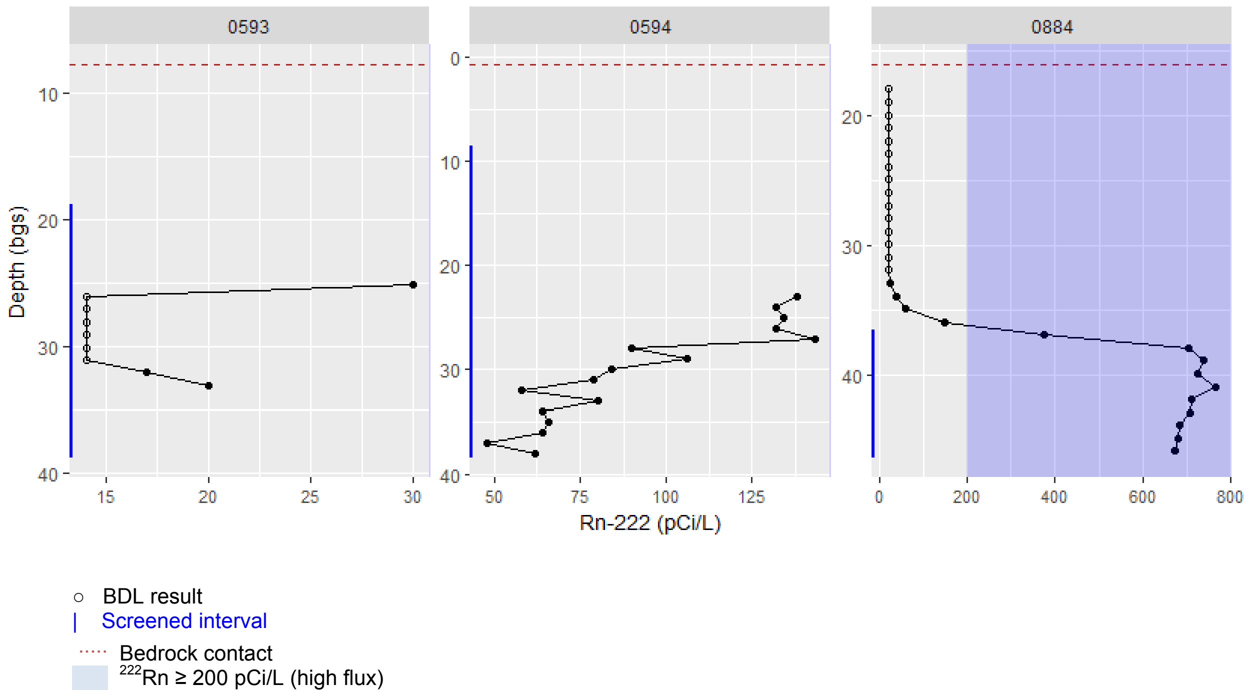

Figure D.1-16. Radon-222 Profiles in Raffinate Ponds Area Wells

Appendix D-2

Vertical Profiles by Well

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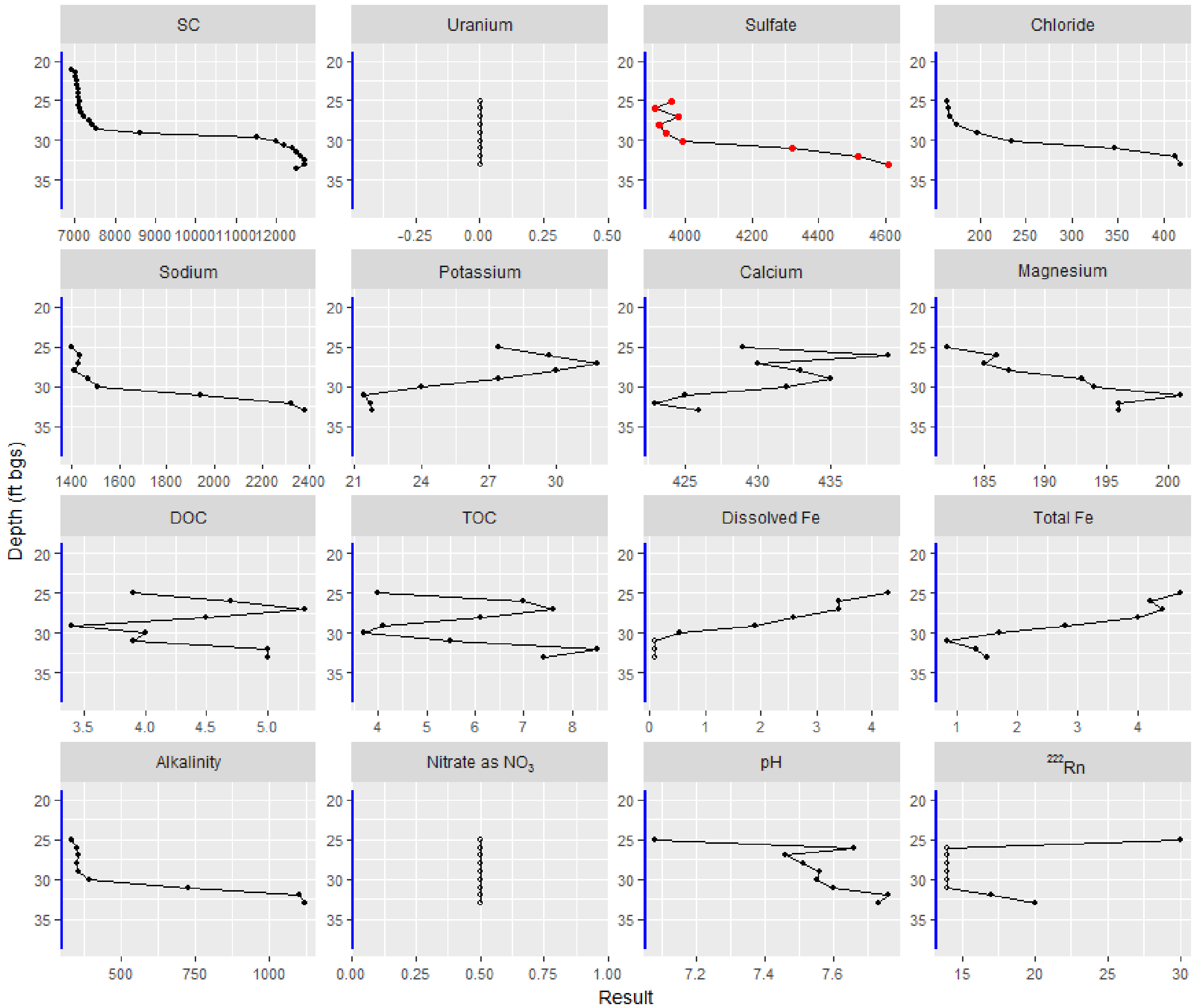
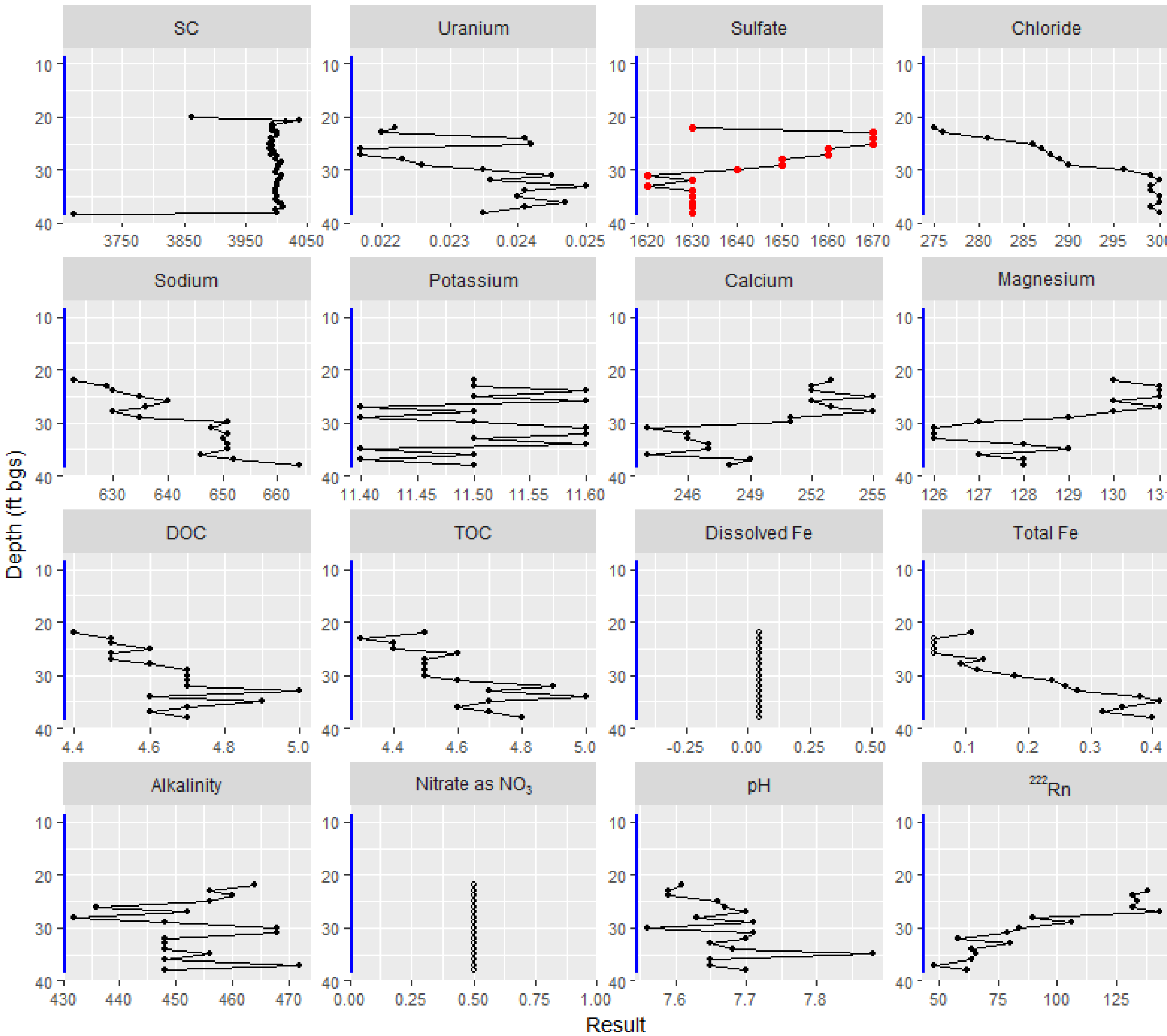


| Screened interval
● Result exceeds corresponding UMTRCA MCL or site background level (DOE 2014c):
0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3
○ BDL result

Note:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$

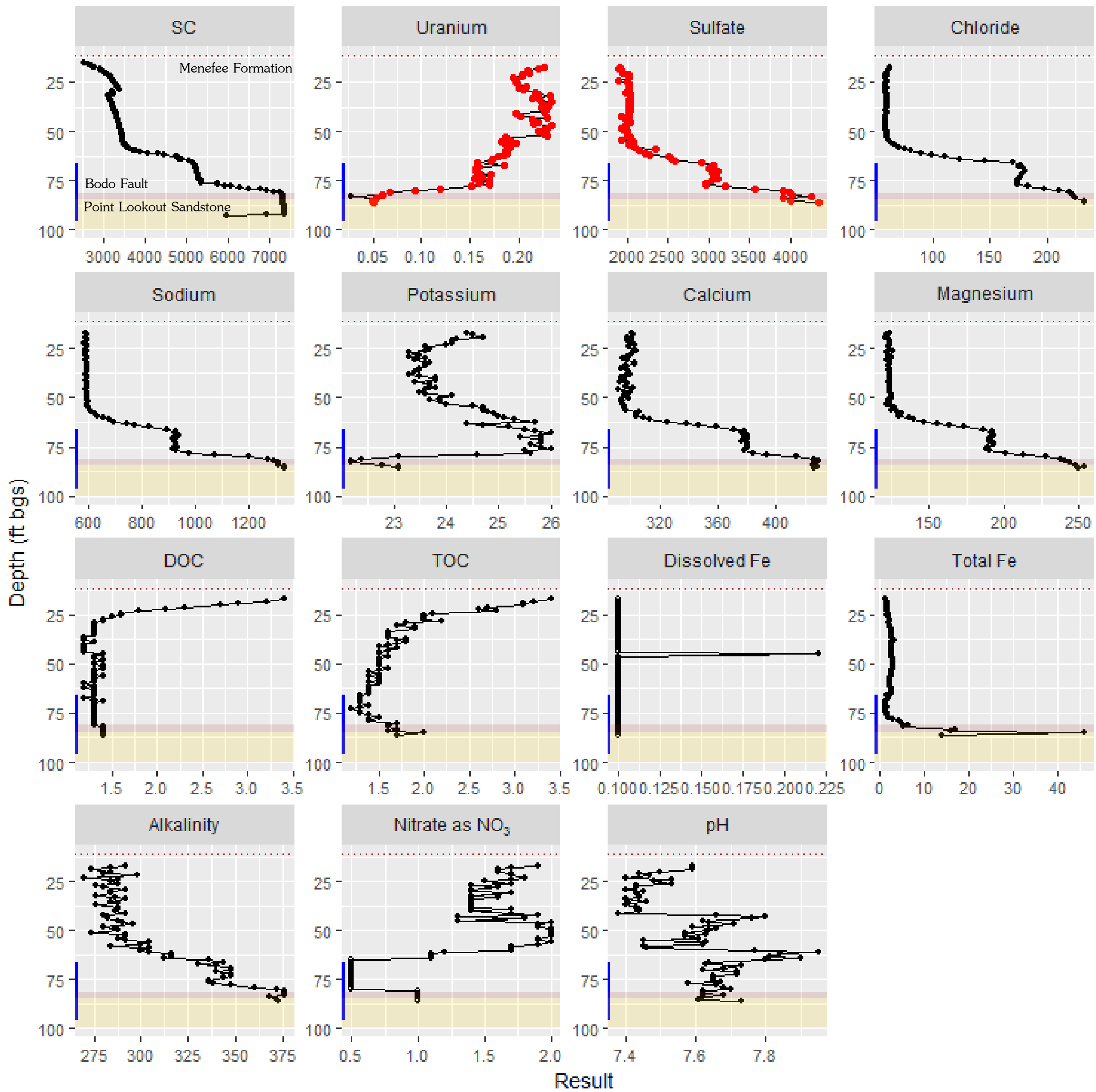
Figure D.2-1. Variable Profiles from Raffinate Ponds Area Well 0593, August–September 2015



| Screened interval
● Result exceeds corresponding UMTRCA MCL or site background level (DOE 2014c): 0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3
○ BDL result

Note:
All units in mg/L except SC (µS/cm), pH, and Rn-222 (pCi/L); alkalinity as $CaCO_3$

Figure D.2-2. Variable Profiles from Raffinate Ponds Area Well 0594, August–September 2015

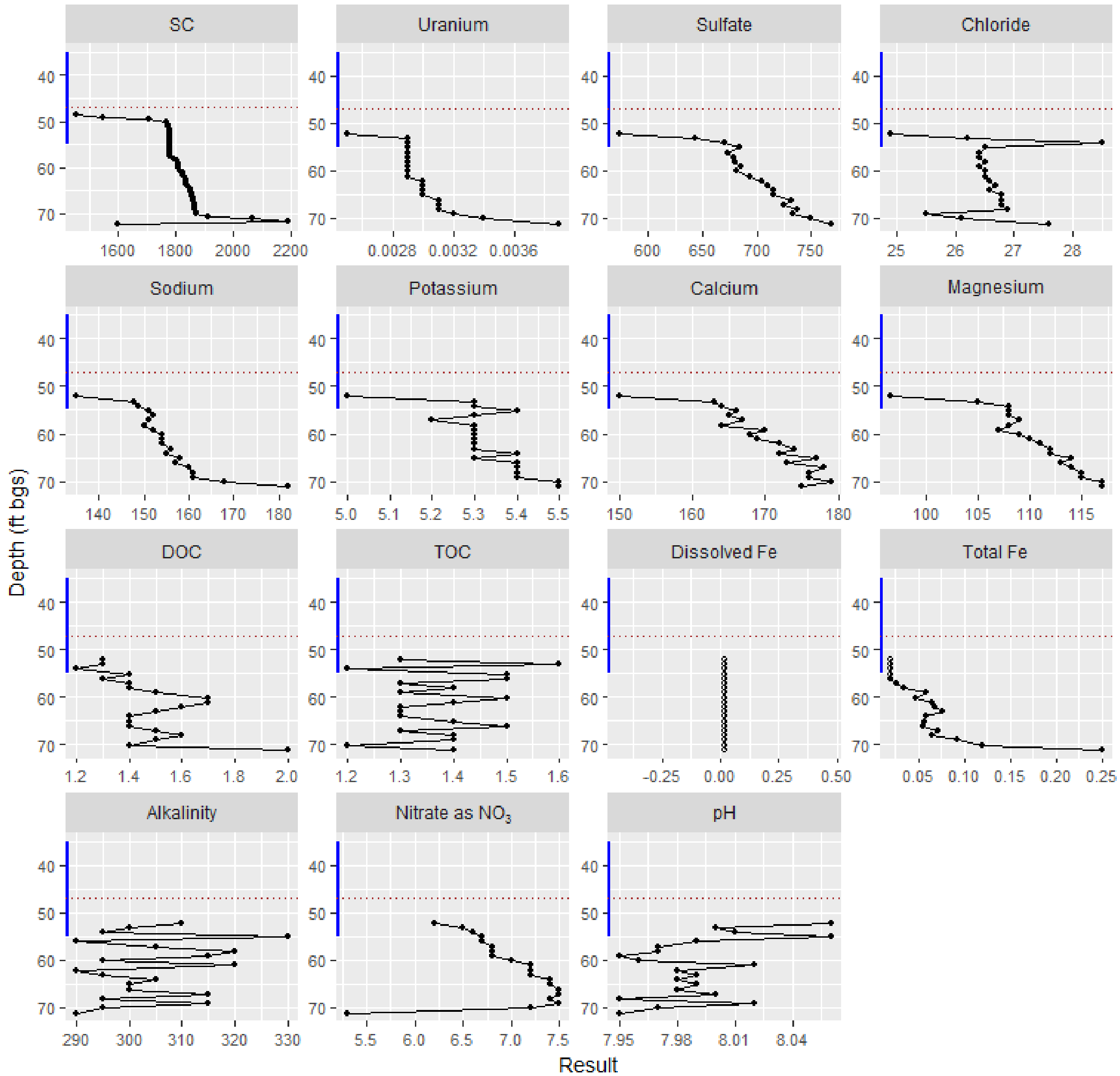


| Screened interval
..... Bedrock (Menefee Formation) contact;

Bodo Fault
Point Lookout Sandstone
● Result exceeds corresponding UMTRCA MCL or site background level (DOE 2014c): 0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3
○ BDL result

Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.
Chemical profiles in this well were incomplete because the pump could not be advanced beyond approximately 86 ft bgs, coinciding with the region of the Point Lookout Sandstone contact.

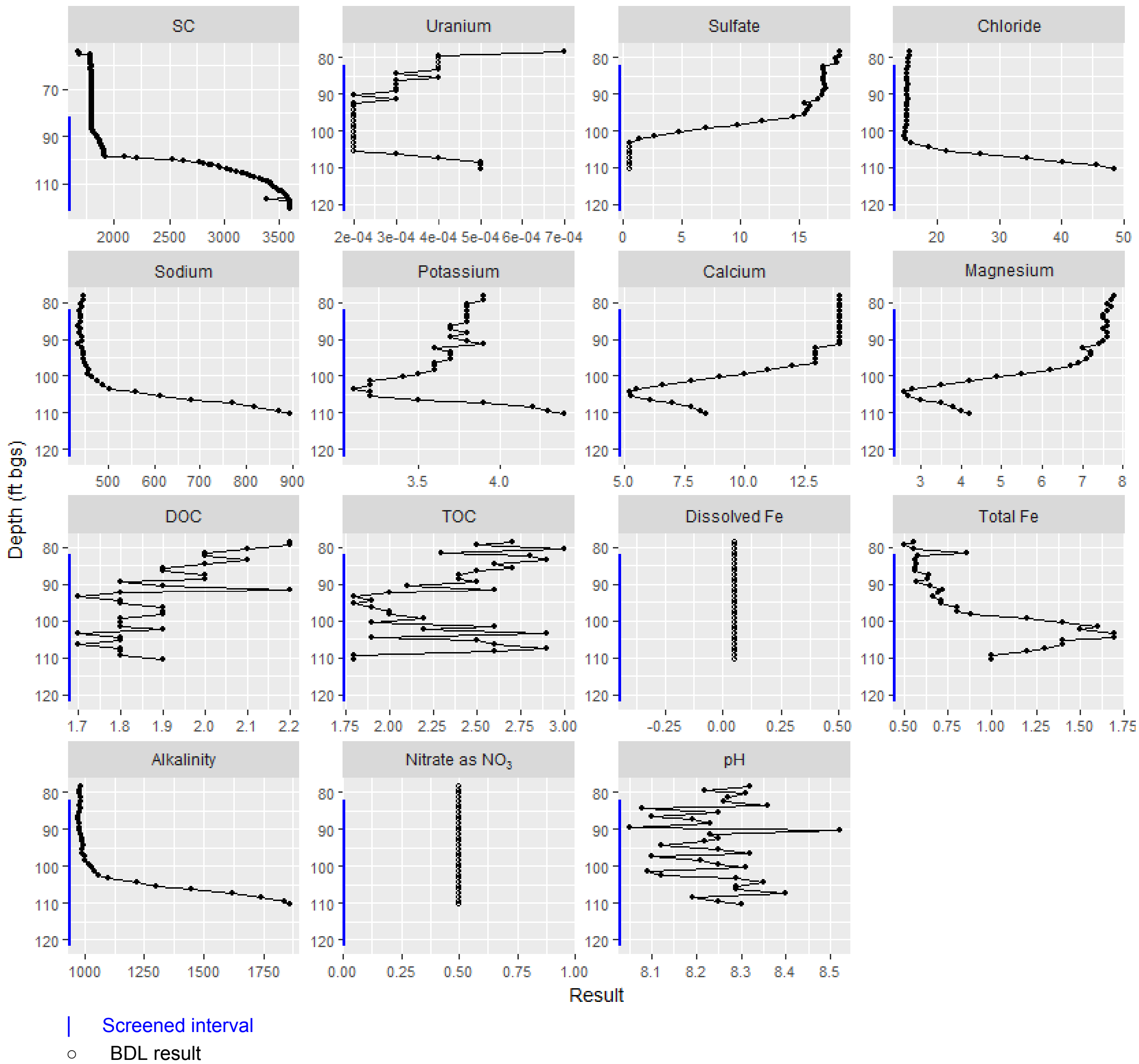
Figure D.2-3. Variable Profiles from Raffinate Ponds Area Well 0598, September 2015



| Screened interval
..... Bedrock (Menefee Formation) contact
○ BDL result

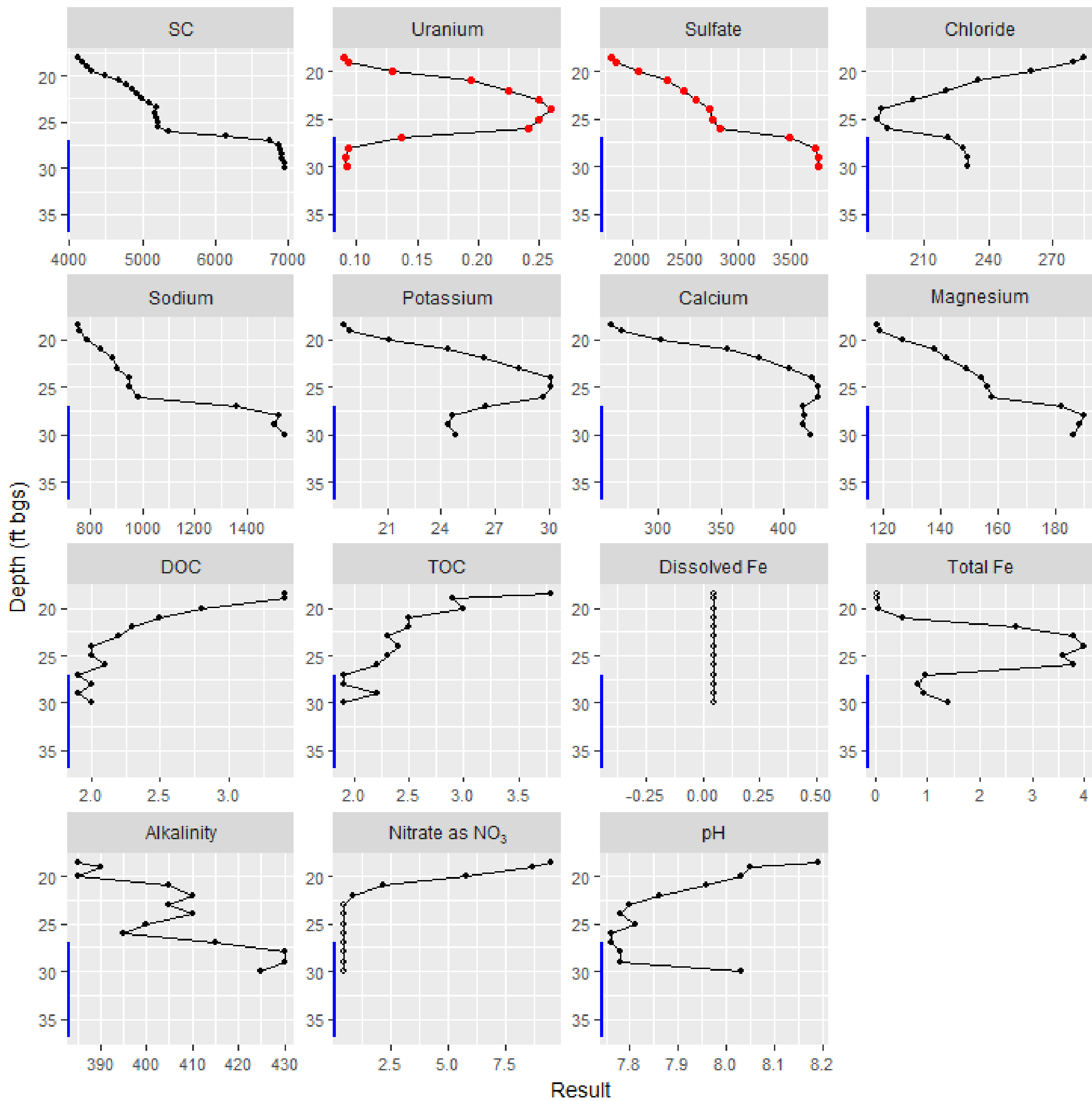
Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$
As shown above, at the time of profiling, most of the water in this well was in the sump.
No result exceeds the corresponding UMTRCA MCL or site background level (DOE 2014c):
0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3

Figure D.2-4. Variable Profiles from Raffinate Ponds Area Well 0607, August 2015



Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$
No result exceeds the corresponding UMTRCA MCL or site background level (DOE 2014c):
0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3

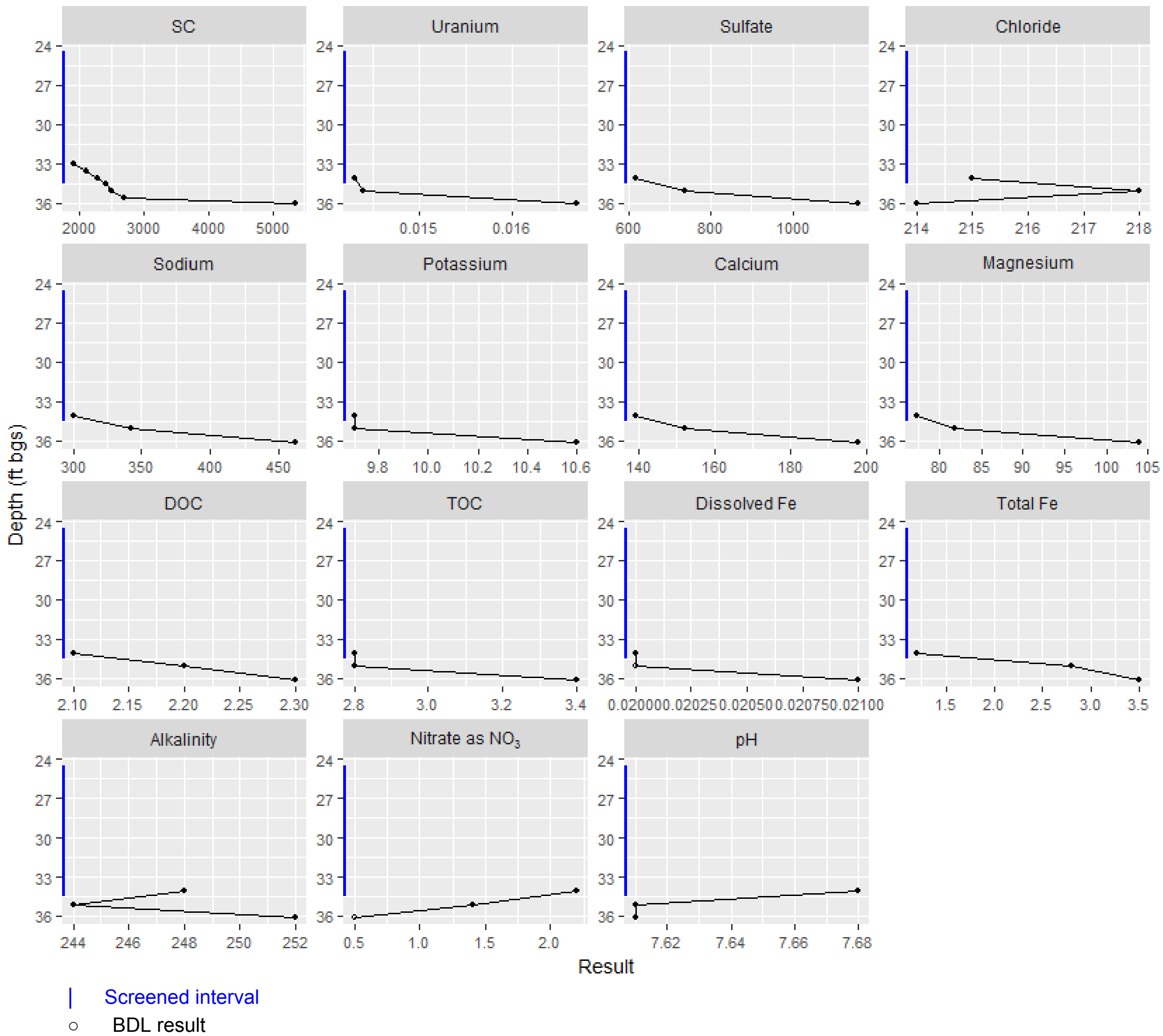
Figure D.2-5. Variable Profiles from Raffinate Ponds Area Point Lookout Sandstone Well 0875 September 2015



| Screened interval
● Result exceeds corresponding UMTRCA MCL or site background level (DOE 2014c): 0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3
○ BDL result

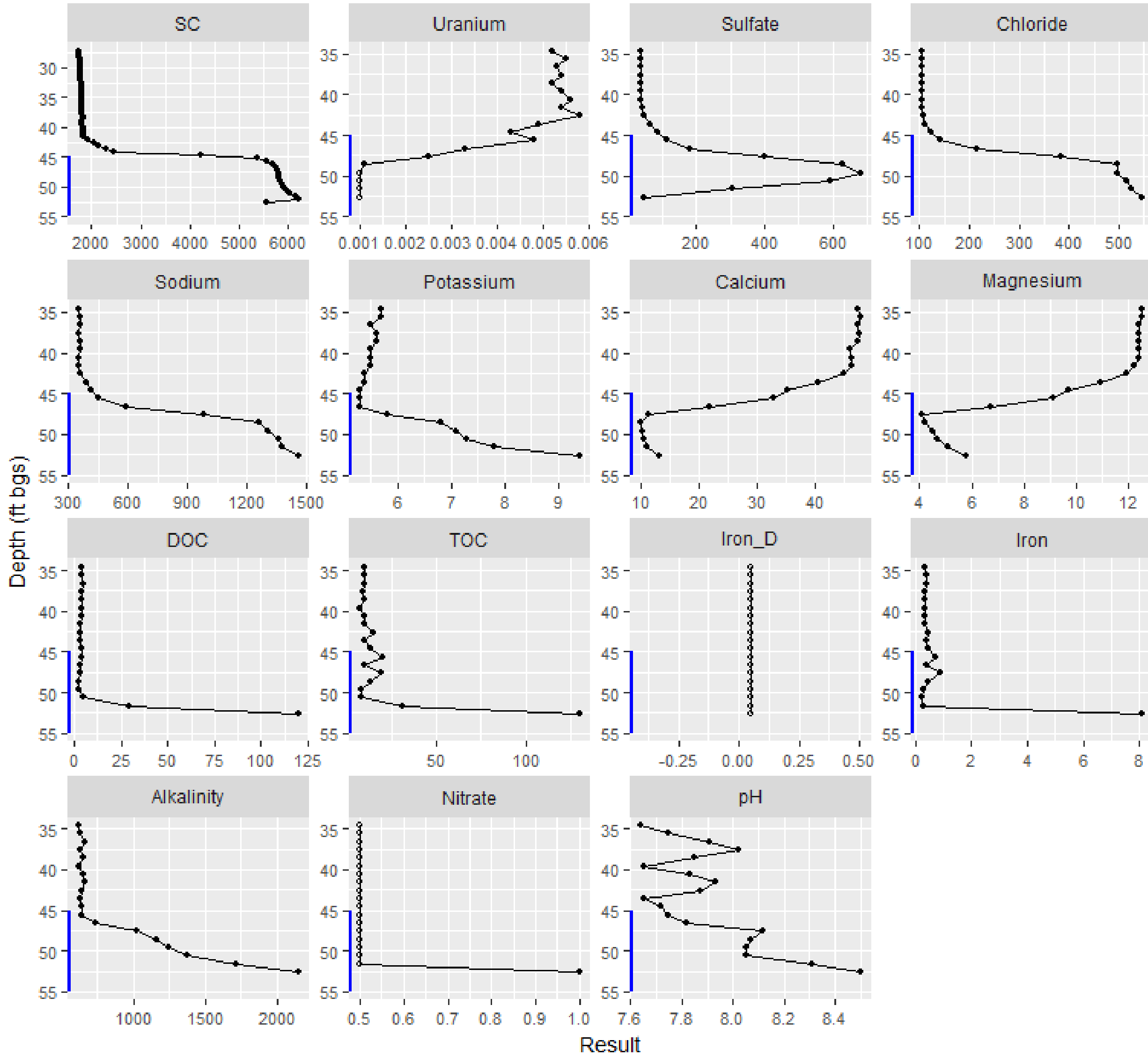
Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$
SC and chemical profiles were incomplete due to an obstruction encountered at about 30.6 ft bgs.

Figure D.2-6. Variable Profiles from Raffinate Ponds Area Well 0879, August 2015



Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$
Too few samples to evaluate (*n* = 3). As found for well 0607, most of the water was in the sump.
No result exceeds the corresponding UMTRCA MCL or site background level (DOE 2014c):
0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3

Figure D.2-7. Variable Profiles from Raffinate Ponds Area Well 0882, August 2015

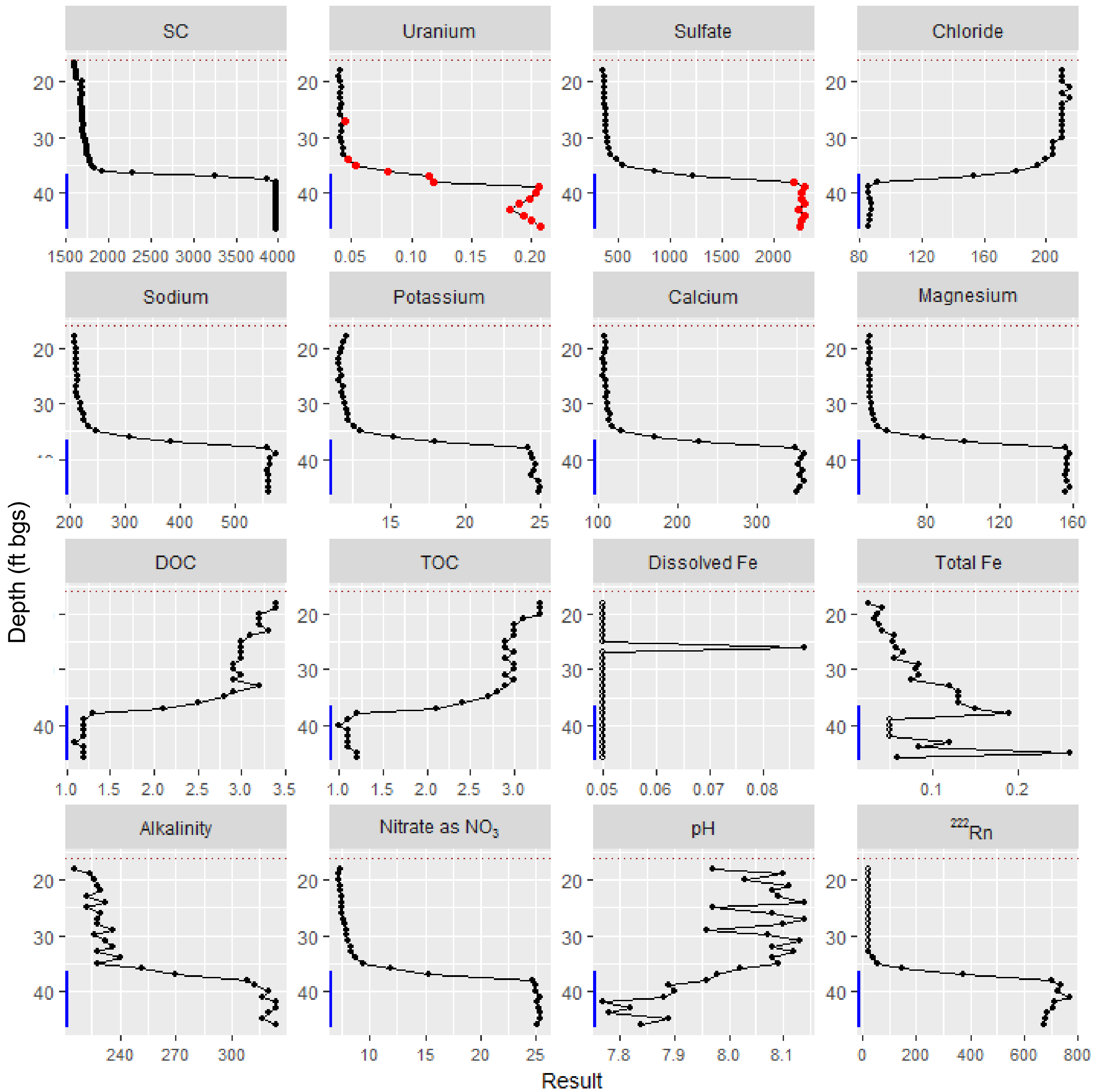


| Screened interval

○ BDL result

Notes:
All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.
No result exceeds the corresponding UMTRCA MCL or site background level (DOE 2014c):
0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3
High DOC and TOC in lowermost sample (120–130 mg/L) possibly attributable to coal bed.

Figure D.2-8. Variable Profiles from Raffinate Ponds Area Well 0883, August 2015



| Screened interval

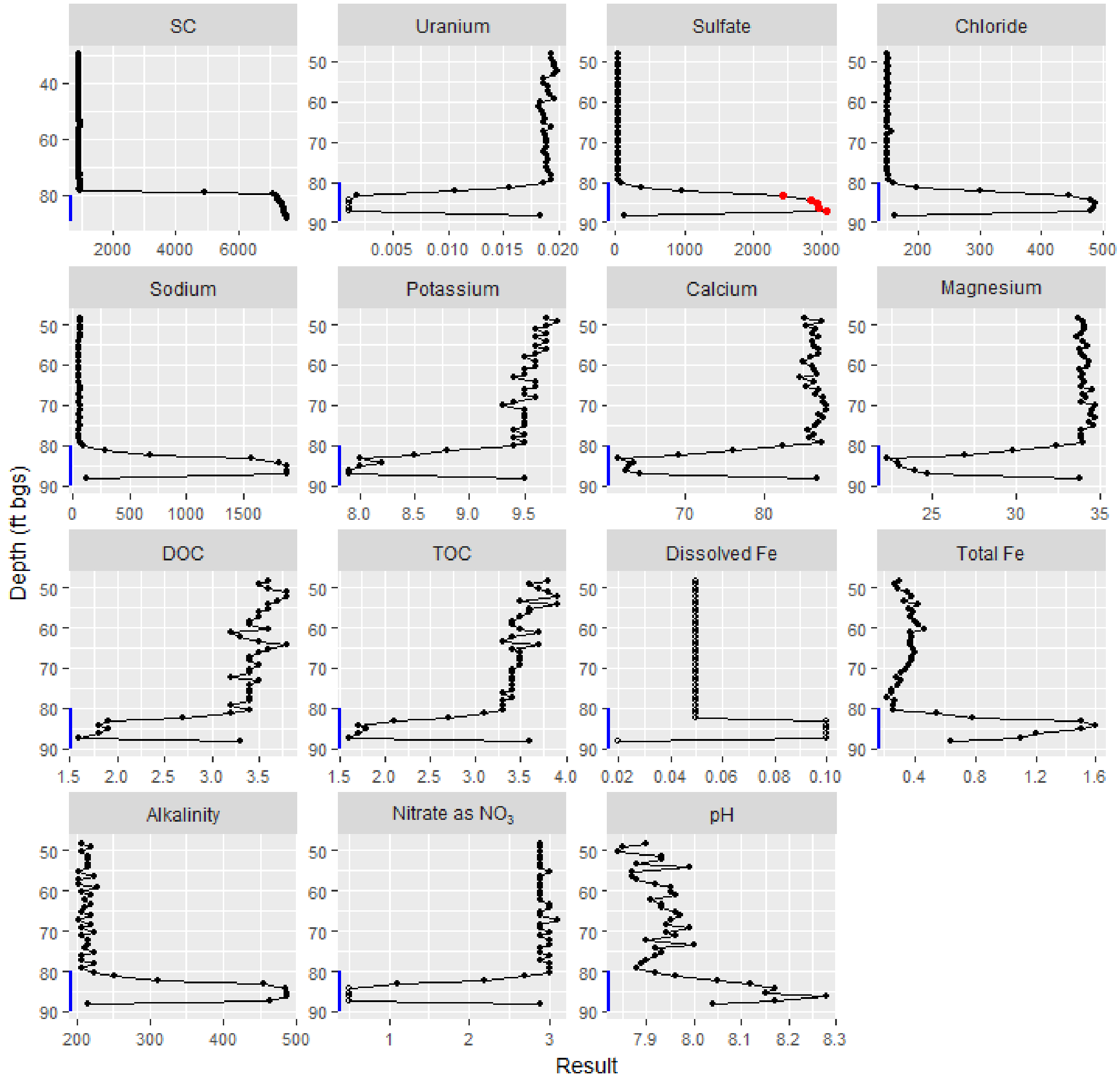
..... Bedrock (Menefee Formation) contact

● Result exceeds corresponding UMTRCA MCL or site background level (DOE 2014c):
0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3

○ BDL result

Note:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$

Figure D.2-9. Variable Profiles from Raffinate Ponds Area Well 0884, August–September 2015



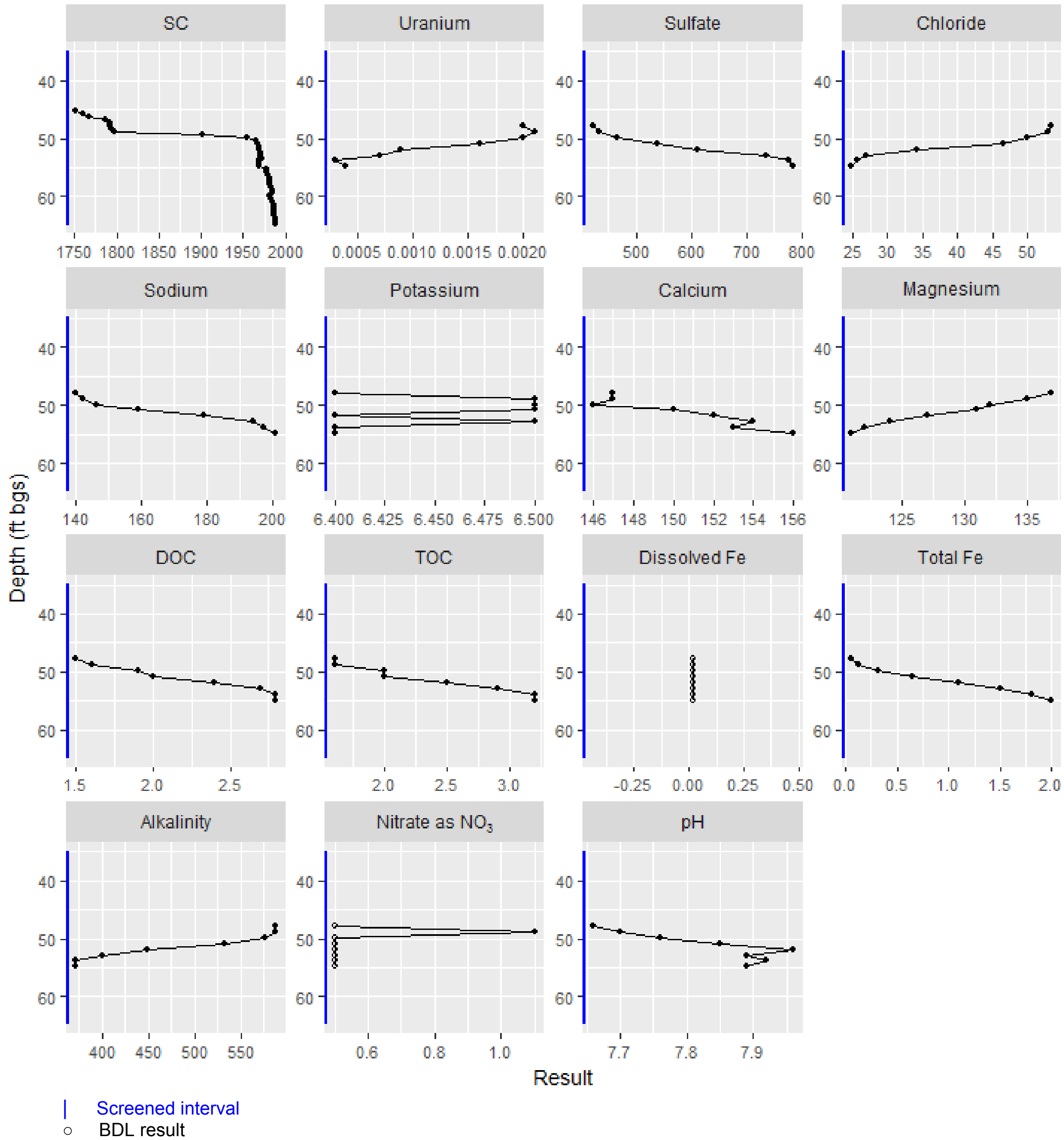
| Screened interval

● Result exceeds corresponding UMTRCA MCL or site background level (DOE 2014c): 0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3

○ BDL result

Note:
All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$

Figure D.2-10. Variable Profiles from Raffinate Ponds Area Well 0889, August 2015



Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$,
No result exceeds the corresponding UMTRCA MCL or site background level (DOE 2014c):
0.044 mg/L uranium, 1276 mg/L sulfate (background); 44 mg/L nitrate as NO_3

Figure D.2-11. Variable Profiles from Raffinate Ponds Area Well 0903, August 2015

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Appendix E

Shiprock Site Floodplain SC and Analyte Profiles

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Preface

Phase II of this study yielded 550 variable profiles for the Shiprock site floodplain wells (36 wells × 15 parameters + 10 ^{222}Rn profiles). The discussion in the main body of the report focused mainly on SC, uranium, sulfate, nitrate, and ^{222}Rn and on those wells with the most variable or interesting profiles. This appendix provides a comprehensive graphical summary of Phase II results for all Shiprock site floodplain well-variable combinations.

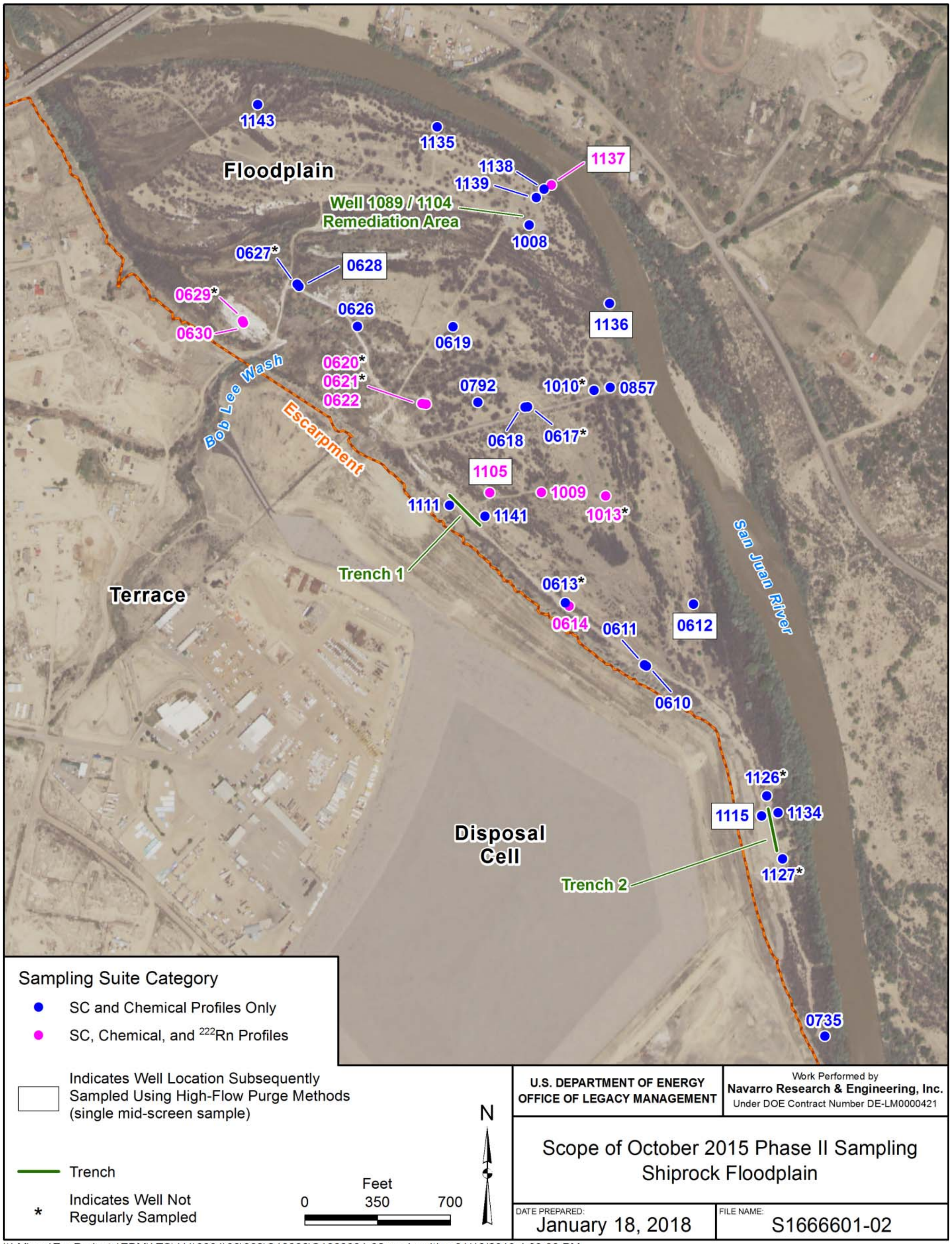
Appendix E-1 plots the profiles by variable, by well. For a given analyte, this presentation allows comparison of profiles between wells. Appendix E-2 provides a different view, plotting profiles of all parameters for each of the 36 wells profiled. When interpreting these figures, it is important to acknowledge the range in values because scales are unique for each well- and variable-specific profile. As such, some profiles initially appearing as being highly variable may just represent random variation if the range of measurements is small. Because this appendix is intended as a stand-alone summary of all Phase II results, some figures from the main body of the report are duplicated. Legend items and abbreviations used globally are listed below.

Legend Items:

|	Screened interval
·····	Bedrock (Mancos Shale) contact
	Mancos Shale (bedrock)
●	Casing
●	Screen
●	Sump
○	BDL result
*	Well not routinely sampled

Abbreviations:

AL	alluvium
BDL	below detection limit (denoted by ○ in plots)
bgs	below ground surface
CV	coefficient of variation
DOC	dissolved organic carbon
Fe	iron
MCL	maximum concentration limit established in 40 CFR 192
mg/L	milligrams per liter
μS/cm	microsiemens per centimeter
SC	specific conductance
TOC	total organic carbon



\\LM\ess\EnvProjects\EBM\LTS\111\0001\08\002\S16666\S1666601-02.mxd smithw 01/18/2018 4:33:06 PM

Figure duplicated from Figure 39 of the main text.

Sample Location Map: Shiprock Site Floodplain Wells Profiled in Phase II

Appendix E-1

Vertical Profiles by Analyte

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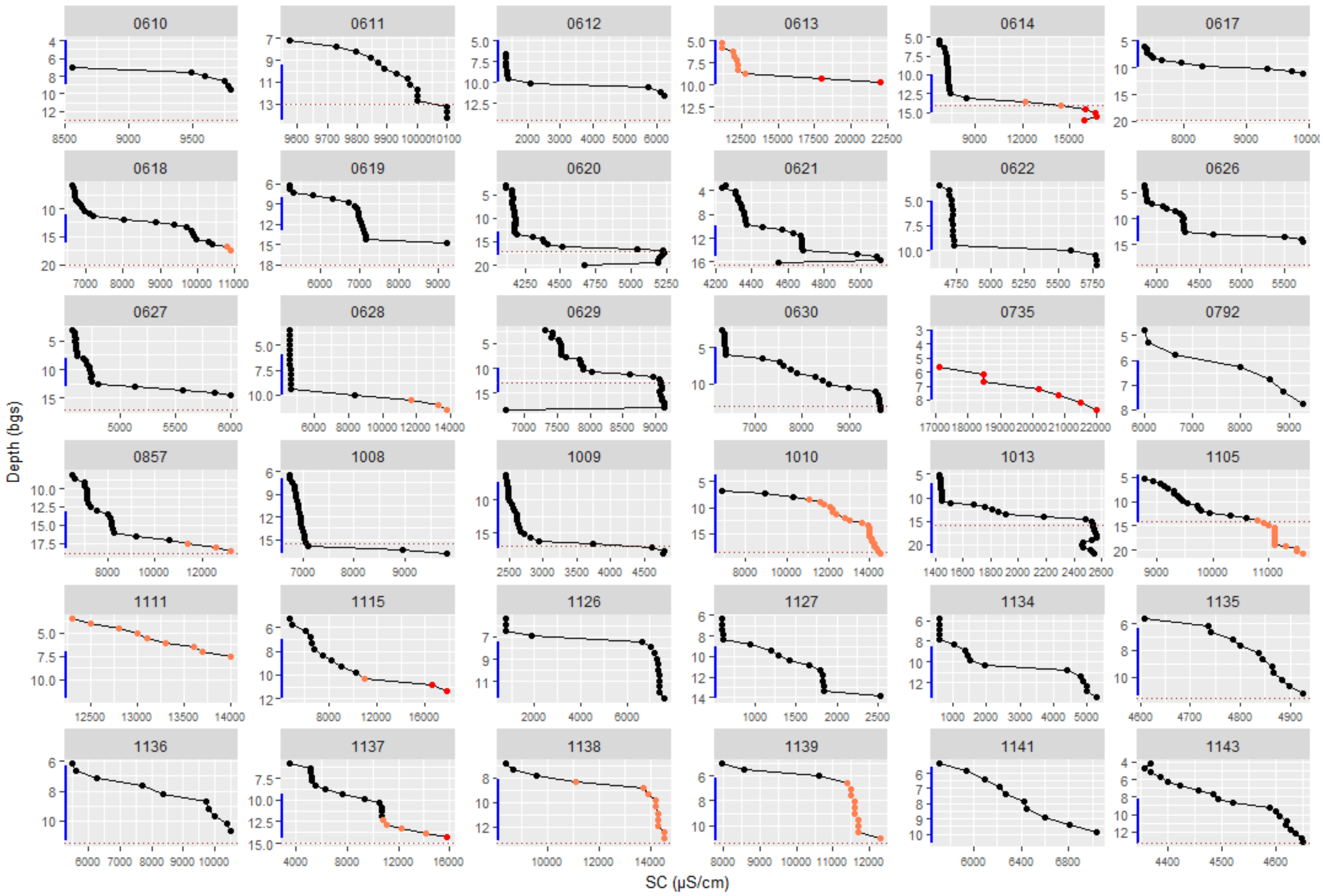
Specific Conductance by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

| screened interval

bedrock contact

Mancos Shale

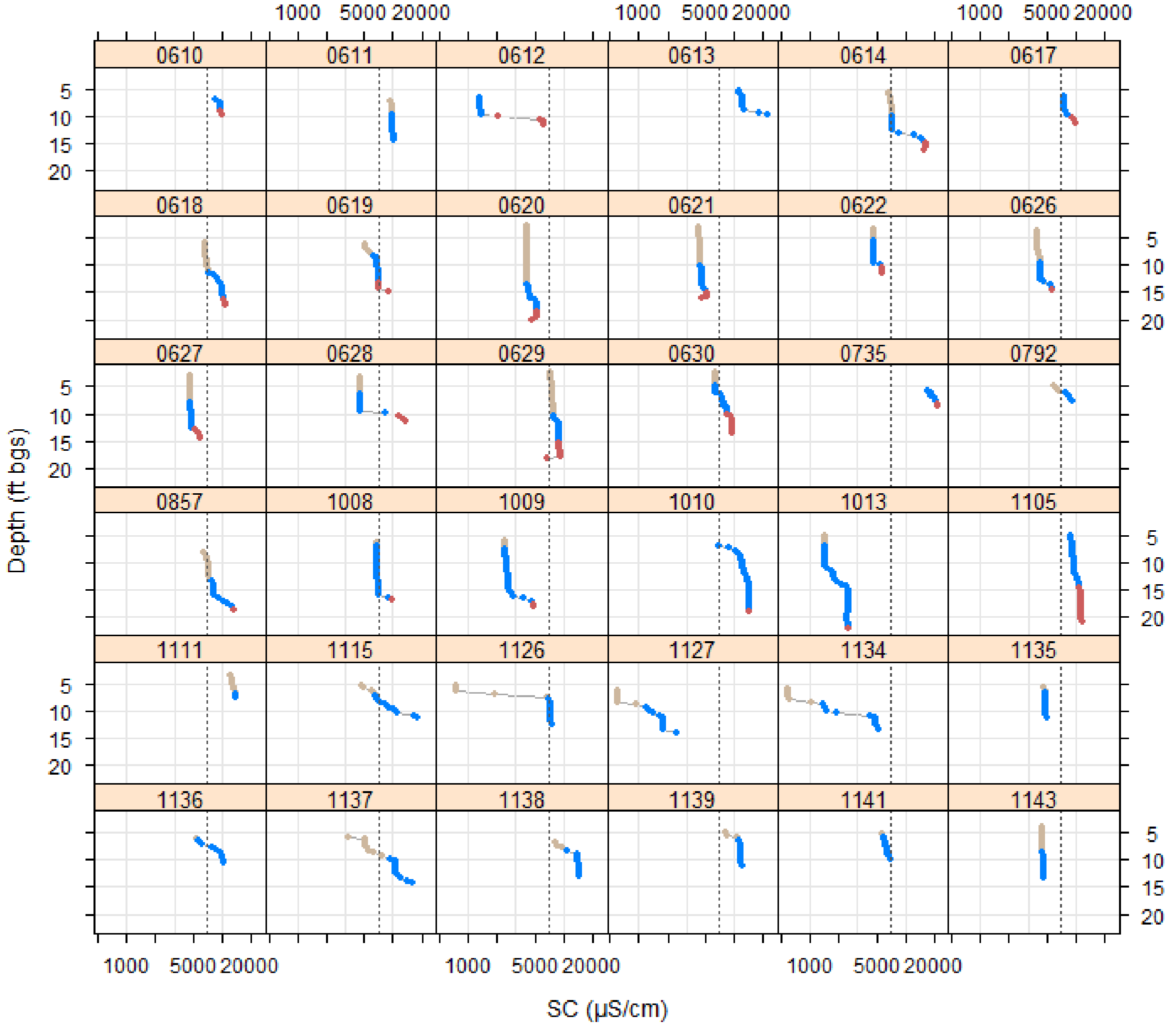
bgs below ground surface

SC specific conductance

To provide a context for interpreting results (i.e., to help identify wells with relatively higher SC), points are color-coded based on the distribution of SC in the Phase II Shiprock site floodplain data set. The mean and standard deviation (SD) were 7003 and 3794 µS/cm, respectively.

- SC ≤ 10,797 µS/cm (mean + 1×SD)
- 10,797 < SC ≤ 14,591 µS/cm (mean + 2×SD)
- SC > 14,591 µS/cm

Specific Conductance Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



Notes:

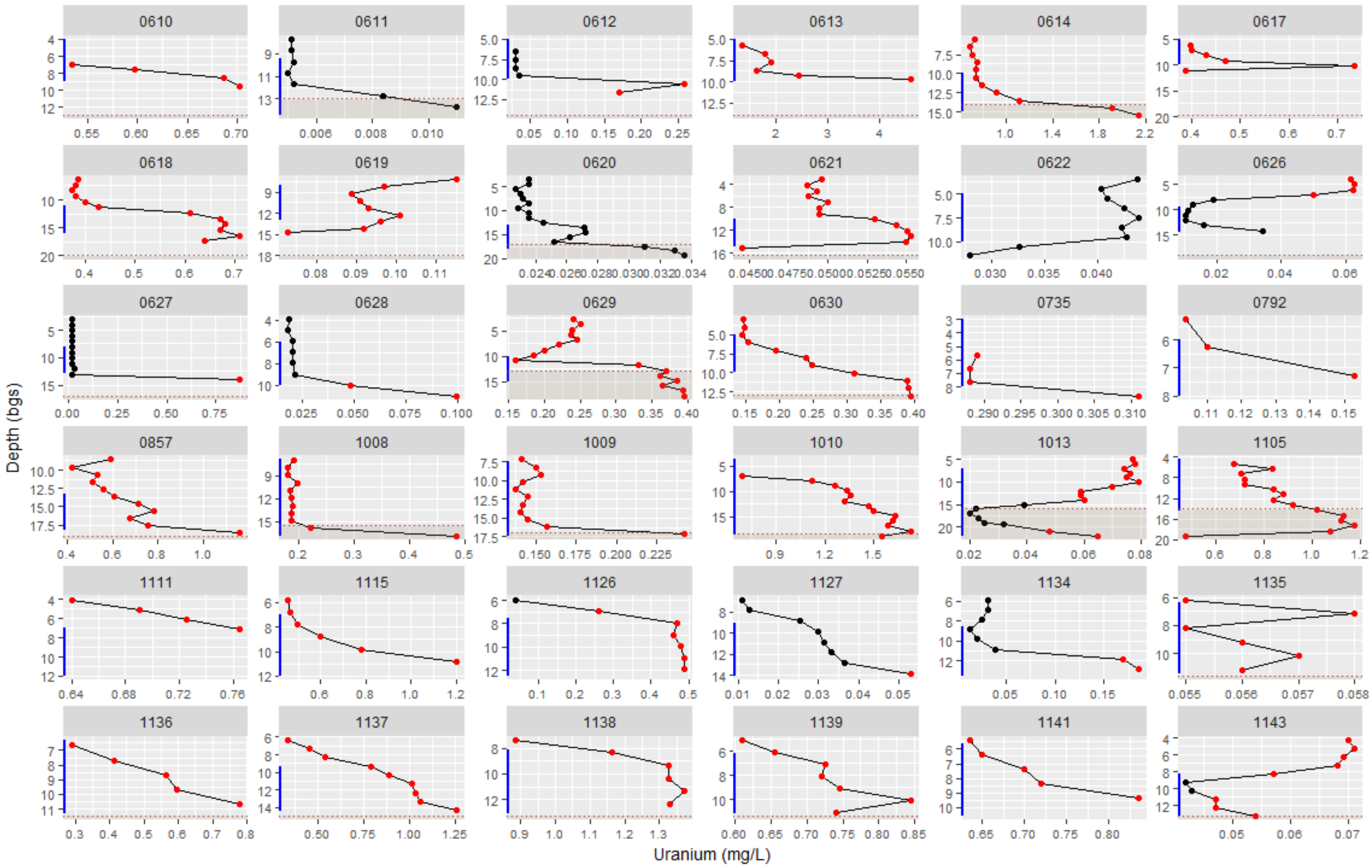
Figure duplicated from Figure 46 in Section 5 of this report
Use of a logarithmic *x*-axis scale may mask the magnitude of change in SC with depth.

- casing
- screen
- sump

- - - mean SC of Phase II Shiprock site floodplain data set (7003 µS/cm)

bgs below ground surface

Uranium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

Figure duplicated from Figure 47 in Section 5 of this report

| screened interval

····· bedrock contact

Mancos Shale

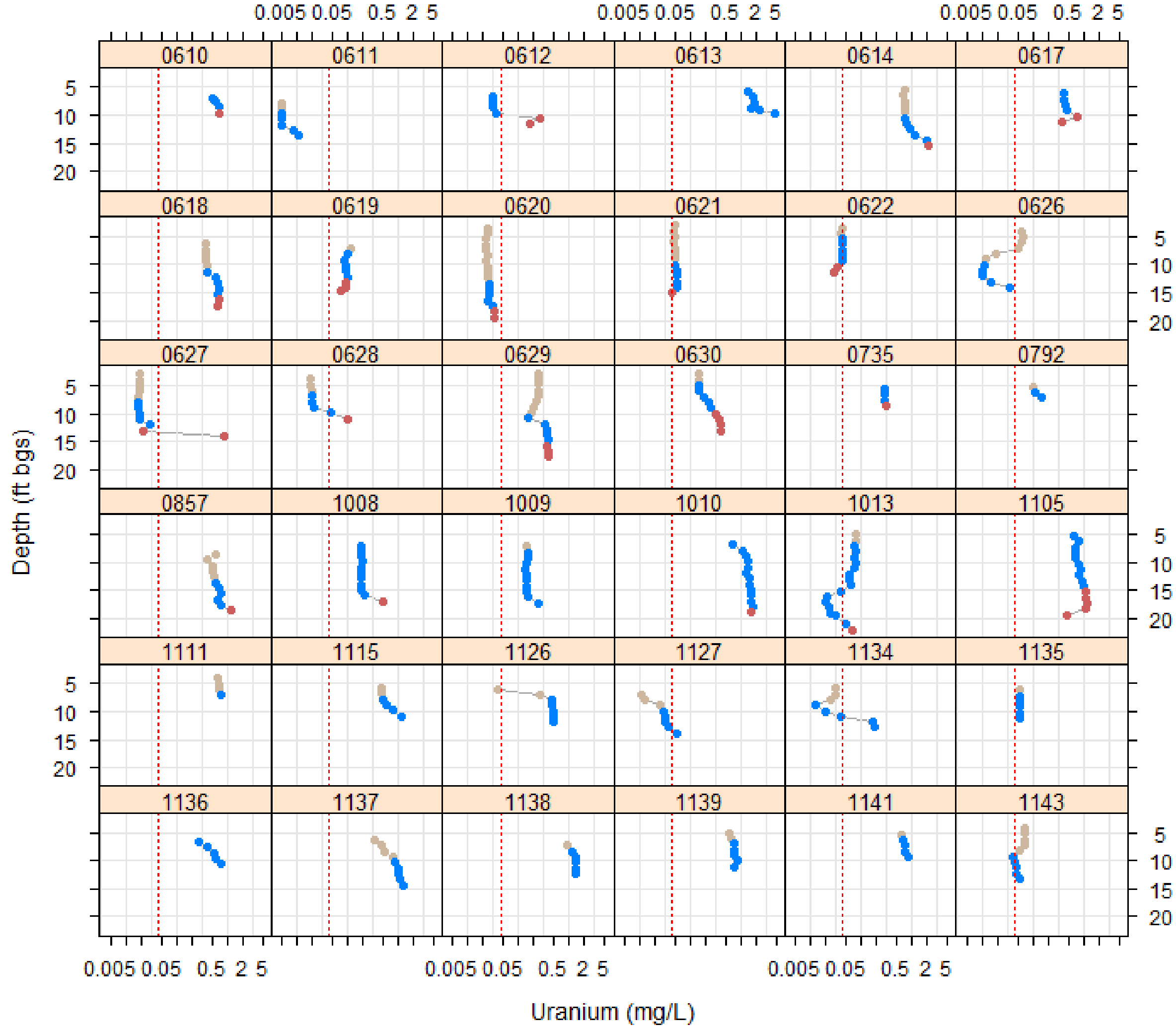
● uranium ≤ 0.044 mg/L 40 CFR 192 standard

● uranium > 0.044 mg/L

○ result below detection limit

bgs below ground surface

Uranium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



Notes:

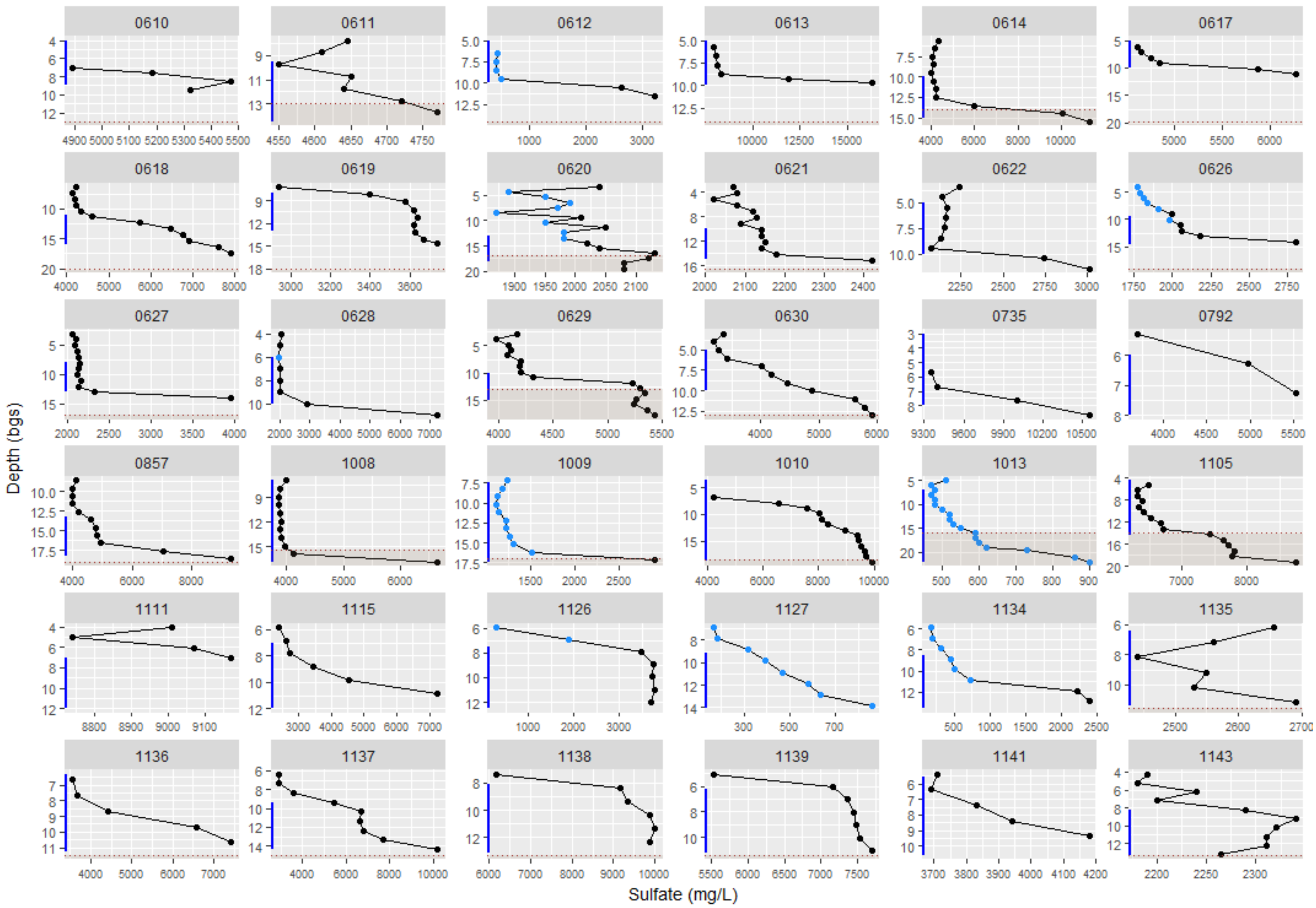
Figure duplicated from Figure 48 in Section 5 of this report
Use of a logarithmic *x*-axis scale may mask the magnitude of change in uranium concentrations with depth.

- casing
- screen
- sump

--- 0.044 mg/L 40 CFR 192 standard

bgs below ground surface

Sulfate Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

Figure duplicated from Figure 49 in Section 5 of this report

| screened interval

······ bedrock contact

Mancos Shale

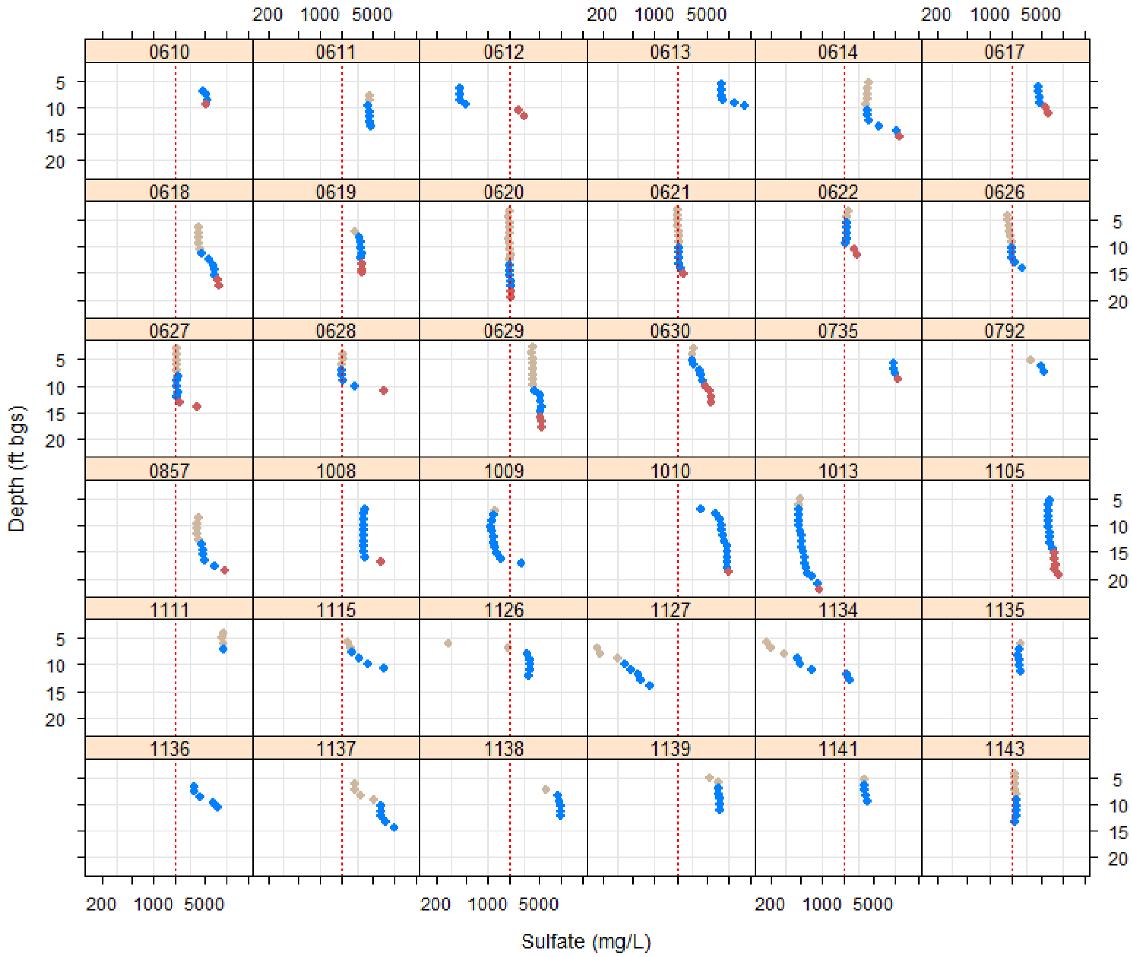
● Sulfate > 2000 mg/L (background)

● Sulfate ≤ 2000 mg/L

○ below detection limit

bgs below ground surface

Sulfate Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



Notes:

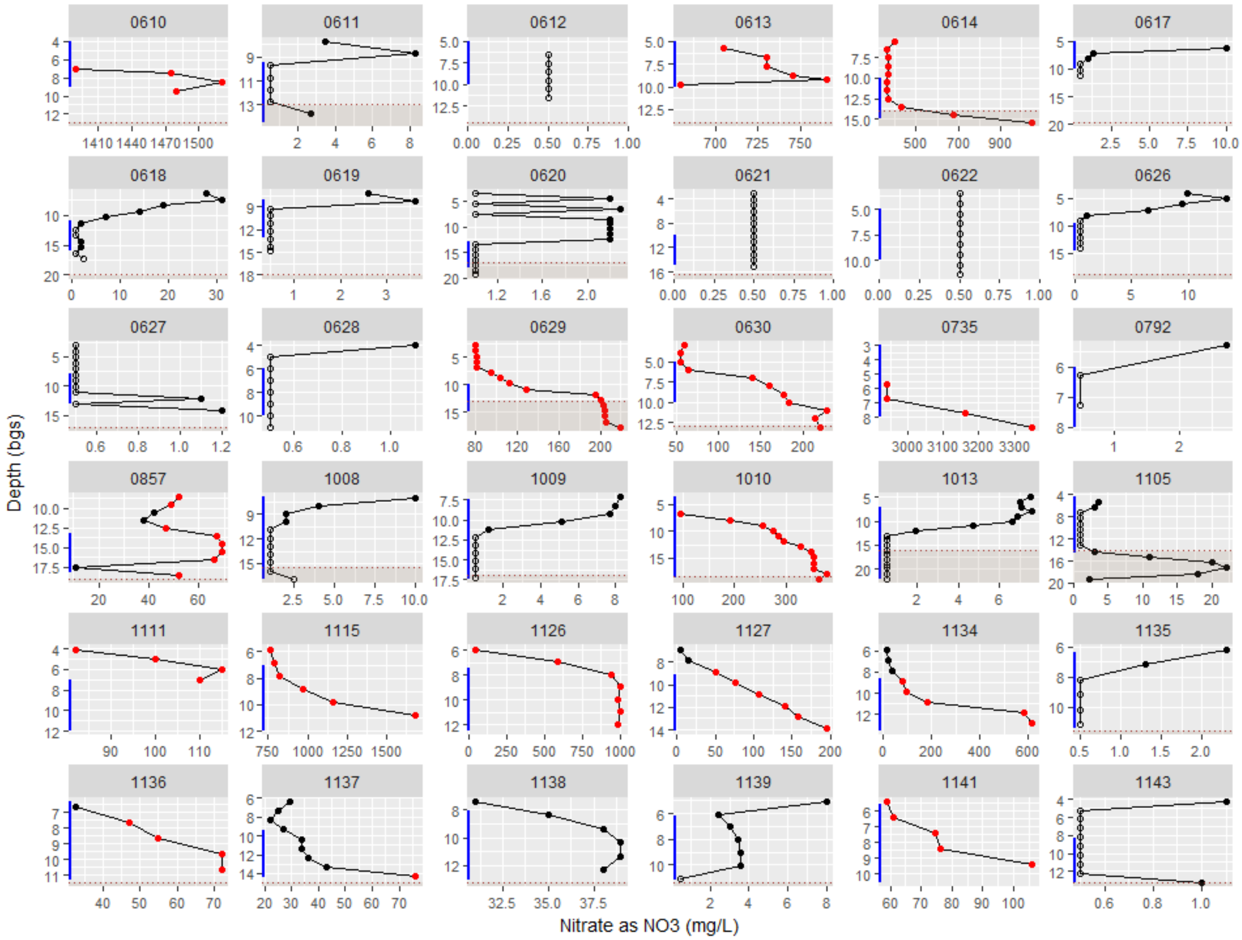
Figure duplicated from Figure 50 in Section 5 of this report
Use of a logarithmic *x*-axis scale may mask the magnitude of change in sulfate concentrations with depth.

- casing
- screen
- sump

--- 2000 mg/L (background)

bgs below ground surface

Nitrate as NO_3 Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

Figure duplicated from Figure 51 in Section 5 of this report

| screened interval

······ bedrock contact

Mancos Shale

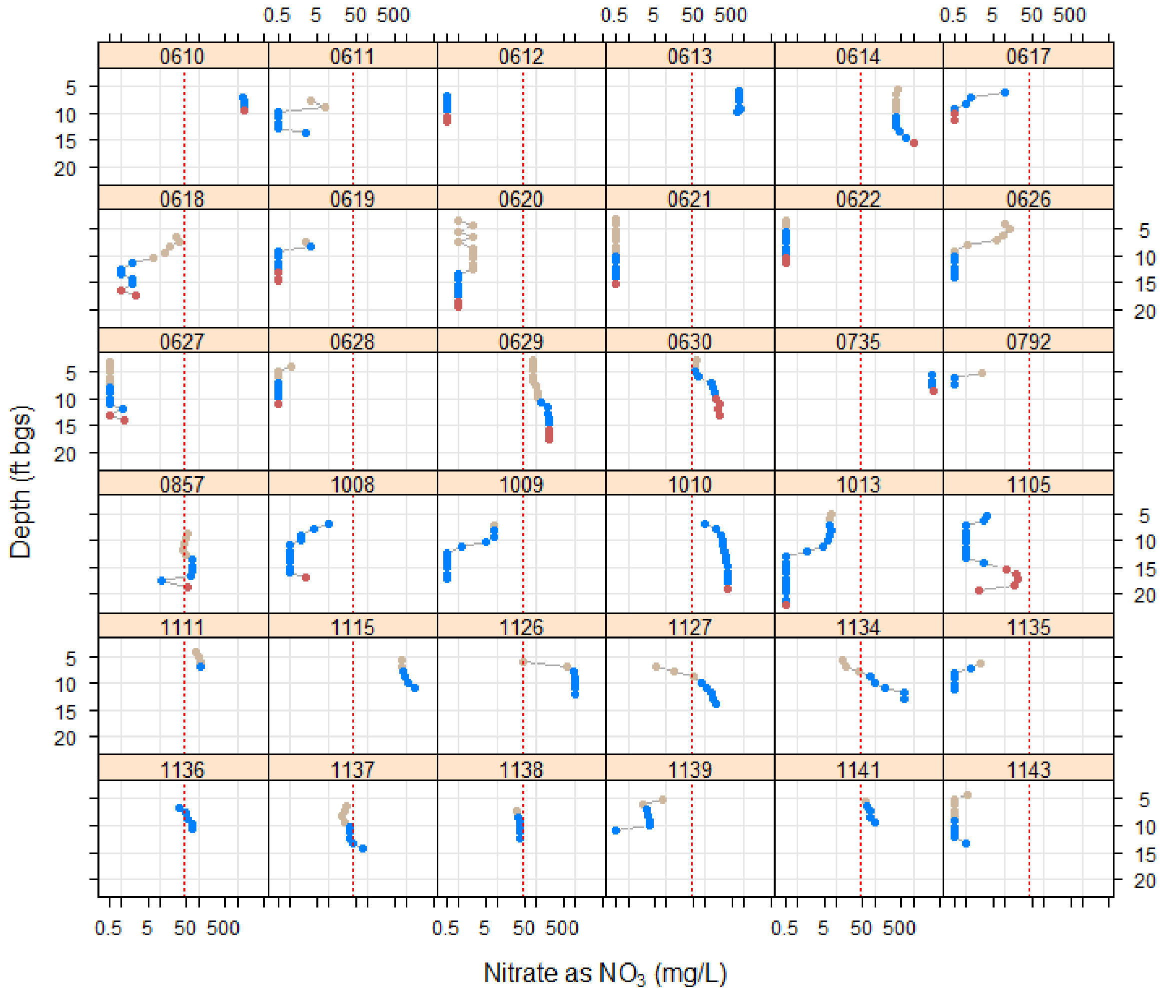
● nitrate as NO_3 ≤ 44 mg/L 40 CFR 192 MCL (converted from 10 mg/L nitrate as N)

● nitrate as NO_3 > 44 mg/L

○ result below detection limit

bgs below ground surface

Nitrate as NO_3 Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



Notes:

Figure duplicated from Figure 52 in Section 5 of this report
Use of a logarithmic *x*-axis scale may mask the magnitude of change in nitrate concentrations with depth.

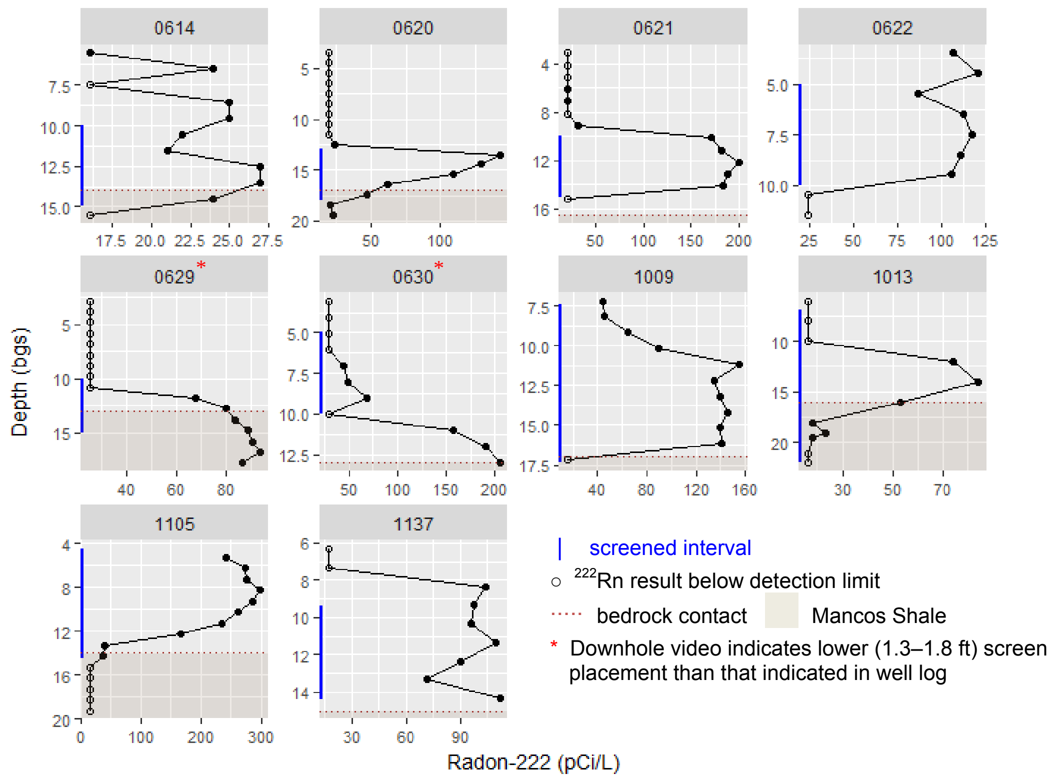
- casing
- screen
- sump

--- 44 mg/L 40 CFR 192 MCL (converted from 10 mg/L nitrate as N)

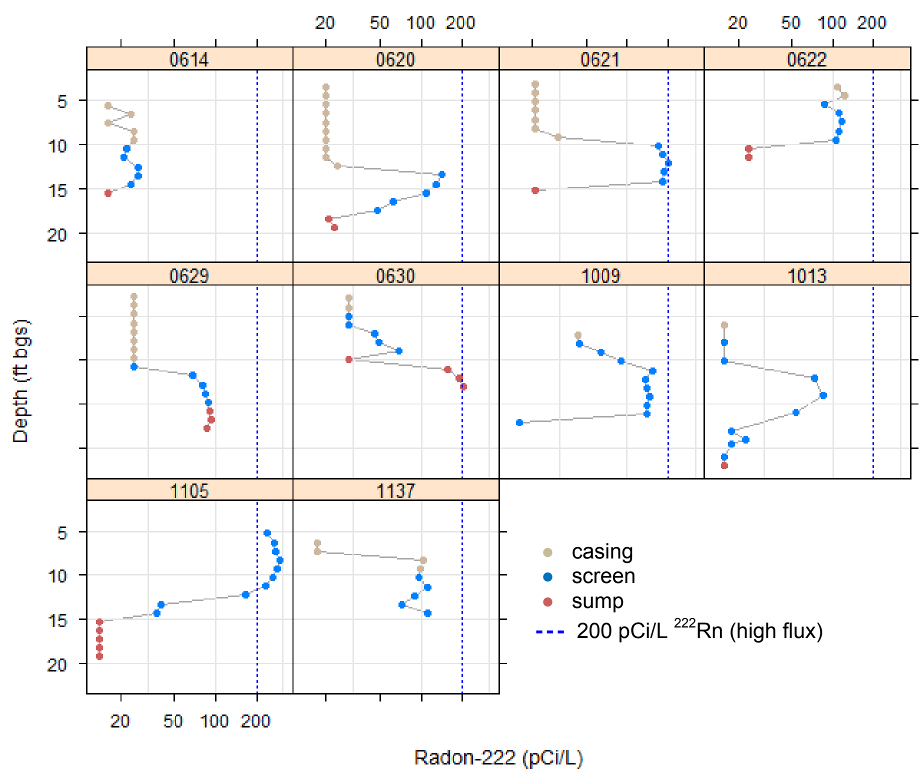
bgs below ground surface

Radon-222 Concentrations by Depth in Shiprock Site Floodplain Wells, Phase II Profiles

a. Unique Scales

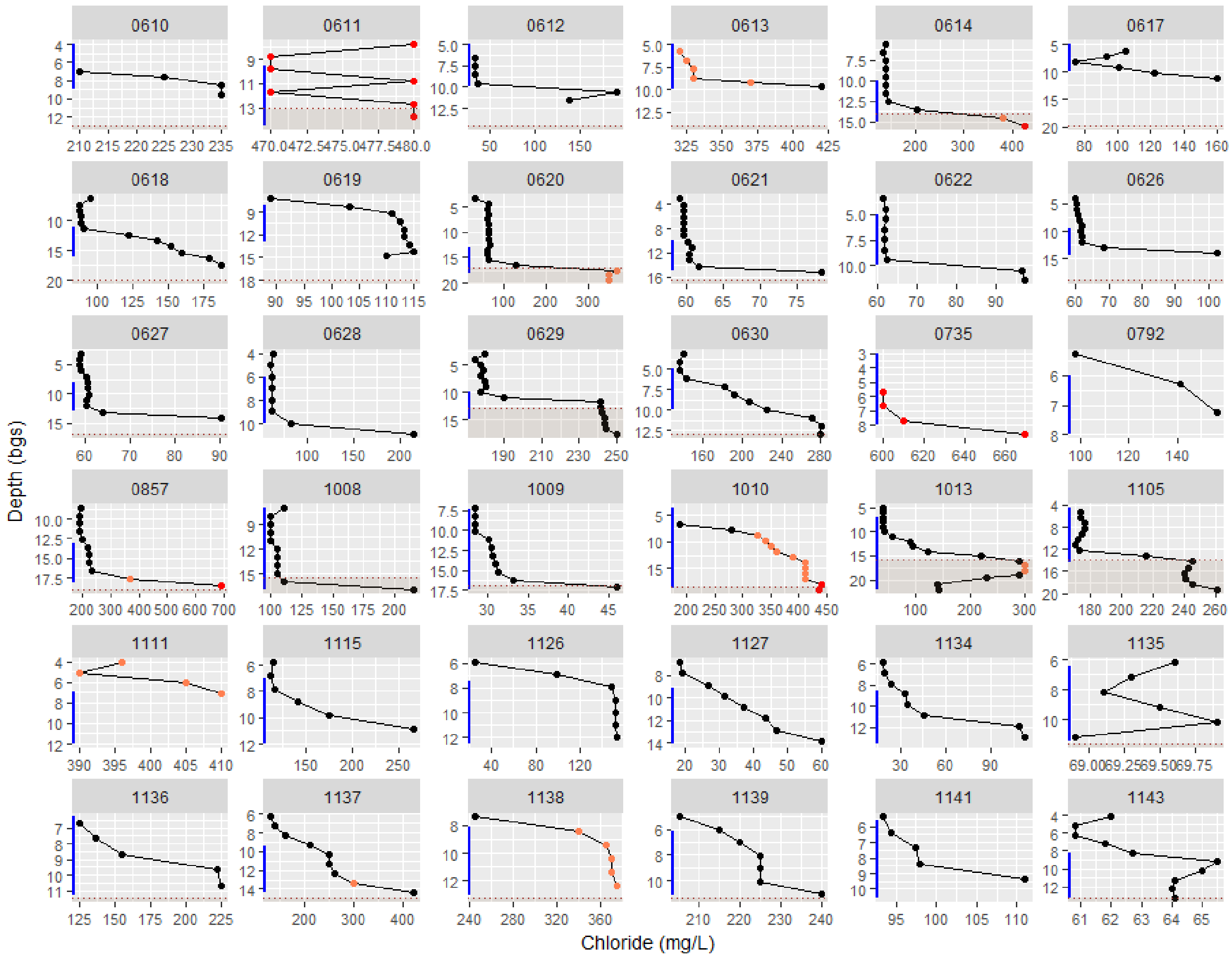


b. Common Scales



***** *Figure adapted from Figure 58 in Section 5 of this report.*

Chloride Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

| screened interval

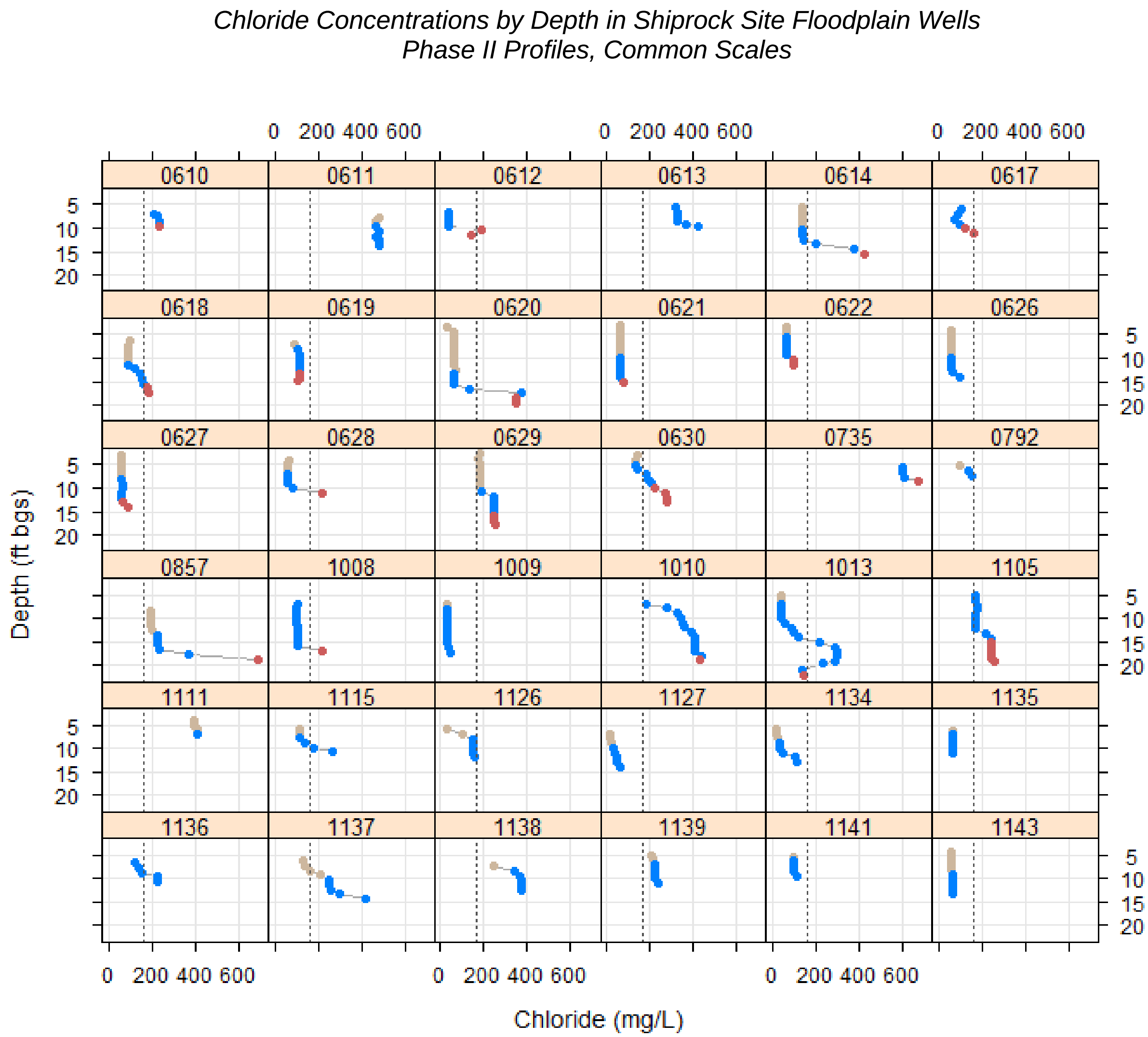
······ bedrock contact

Mancos Shale

bgs below ground surface

To provide a context for interpreting results (i.e., to help identify wells with relatively higher chloride concentrations), points are color-coded based on the distribution of chloride in the Phase II Shiprock site floodplain data set. The mean and standard deviation (SD) were 163.4 and 128.3 mg/L, respectively.

- chloride ≤ 291.7 mg/L (mean + 1×SD)
- 291.7 < chloride ≤ 420 mg/L (mean + 2×SD)
- chloride > 420 mg/L



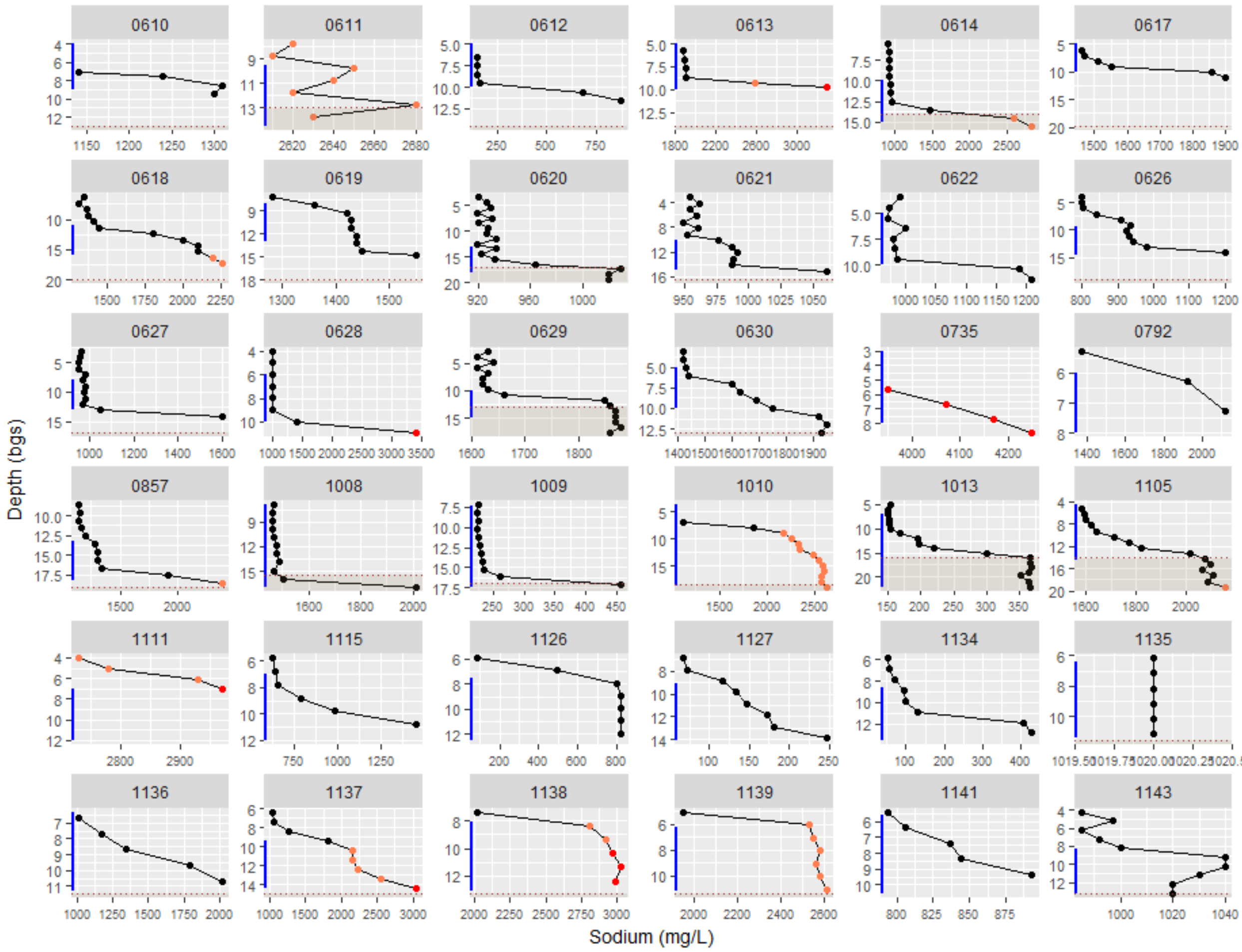
Notes:

- casing
- screen
- sump

--- mean chloride concentration in Phase II Shiprock site floodplain data set (163.4 mg/L)

bgs below ground surface

Sodium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

| screened interval

····· bedrock contact

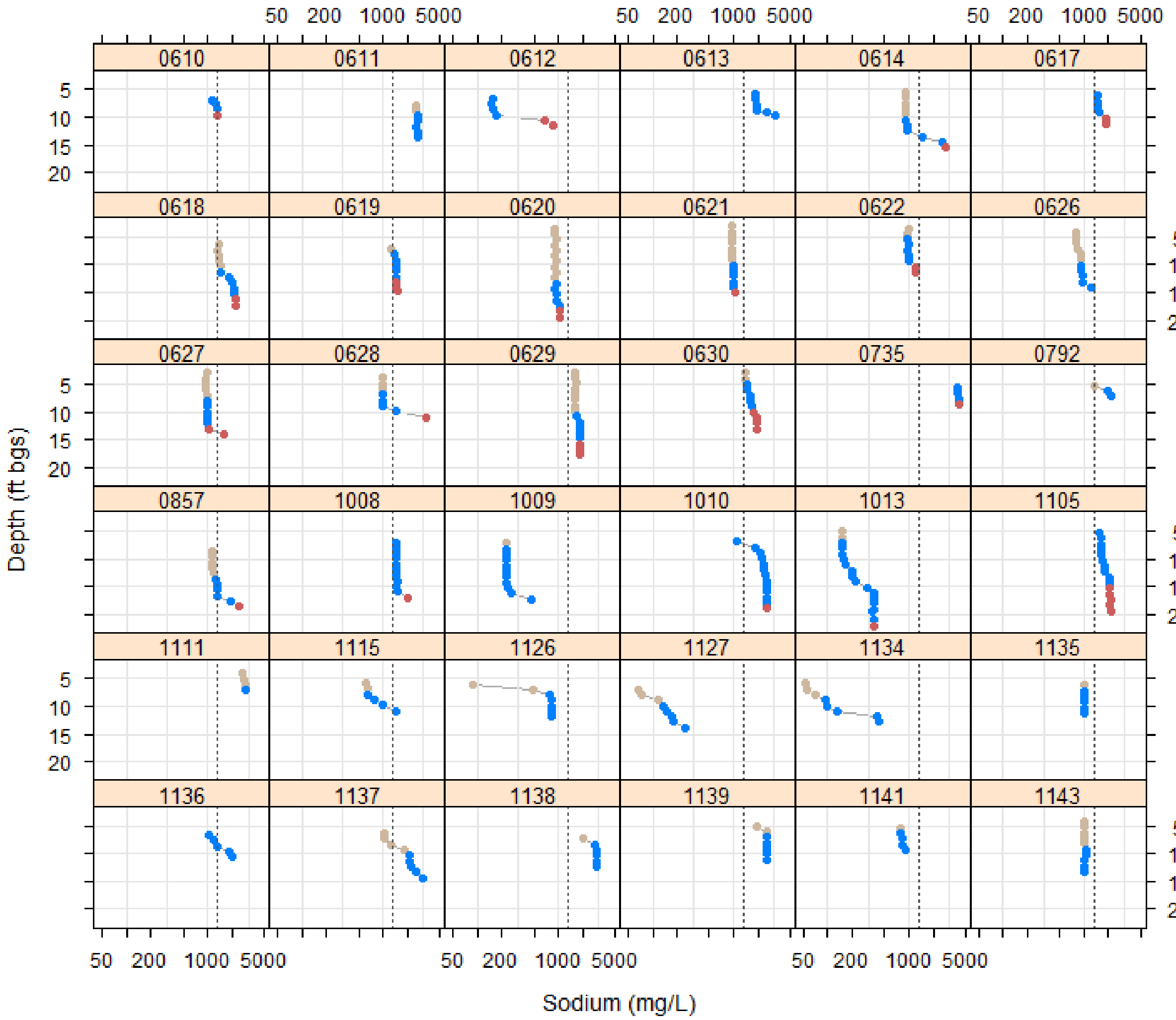
Mancos Shale

bgs below ground surface

To provide a context for interpreting results, points are color-coded based on the distribution of sodium in the Phase II Shiprock site floodplain data set. The mean and standard deviation (SD) were 1341 and 807 mg/L, respectively.

- sodium ≤ 2148 mg/L (mean + 1×SD)
- 2148 < sodium ≤ 2955 mg/L (mean + 2×SD)
- sodium > 2955 mg/L

Sodium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



Notes:

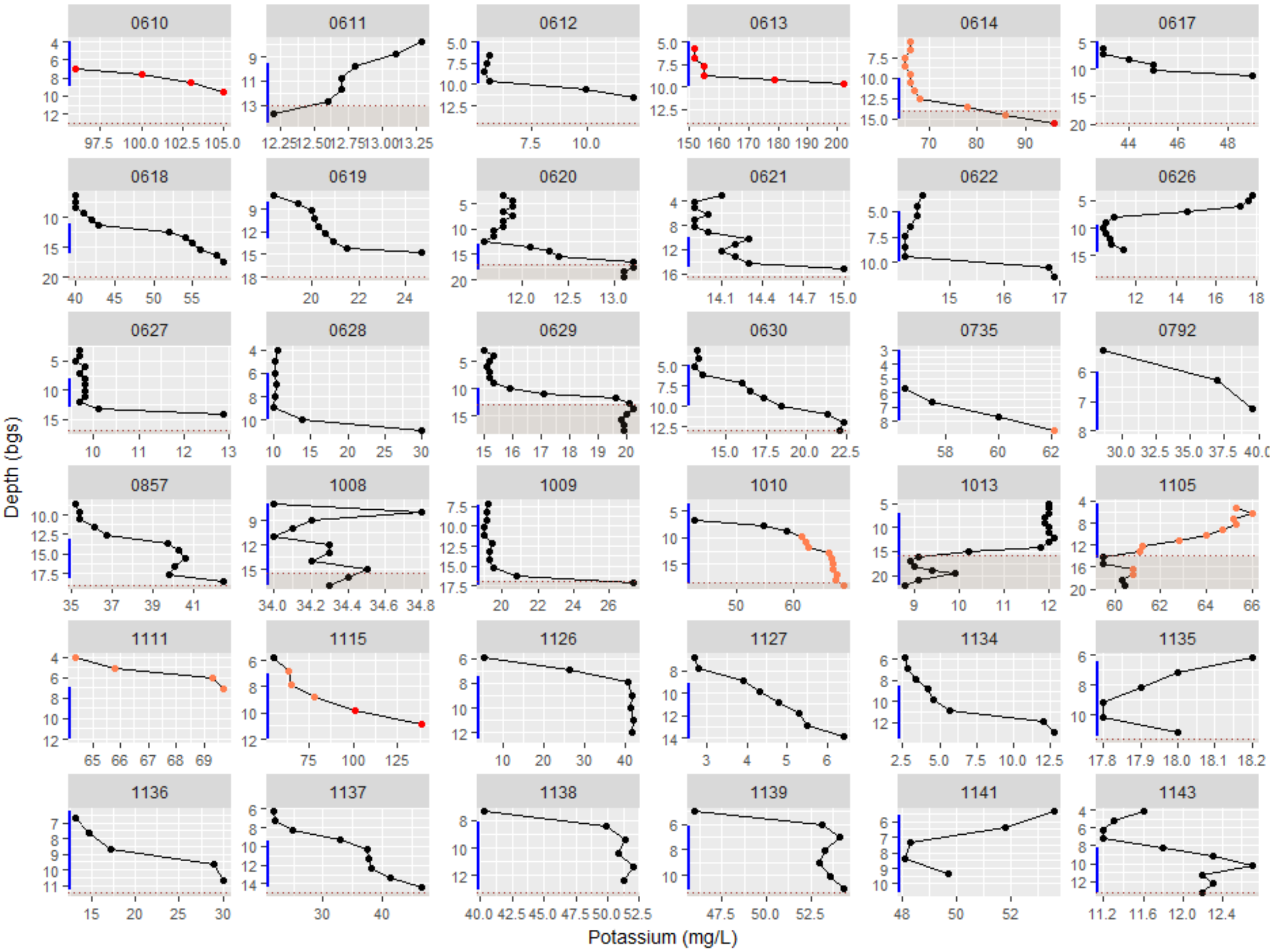
Use of a logarithmic *x*-axis scale may mask the magnitude of change in sodium concentrations with depth.

- casing
- screen
- sump

--- mean sodium concentration in Phase II Shiprock site floodplain data set (1341 mg/L)

bgs below ground surface

Potassium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

| screened interval

⋯⋯ bedrock contact

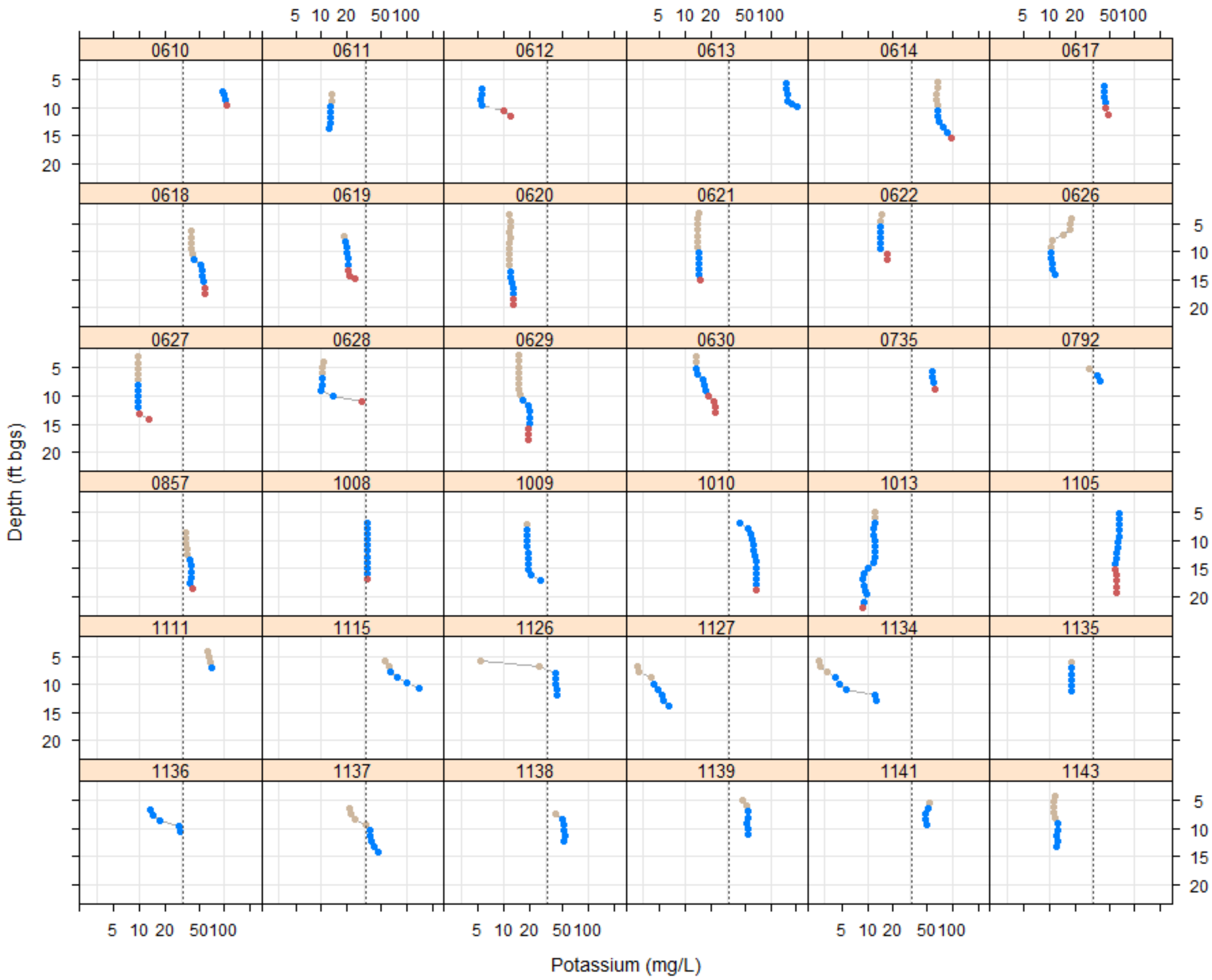
Mancos Shale

bgs below ground surface

To provide a context for interpreting results, points are color-coded based on the distribution of potassium in the Phase II Shiprock site floodplain data set. The mean and standard deviation (SD) were 32.8 and 29.6 mg/L, respectively.

- potassium ≤ 62.4 mg/L (mean + 1×SD)
- 62.4 < potassium ≤ 92 mg/L (mean + 2×SD)
- potassium > 92 mg/L

Potassium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



Notes:

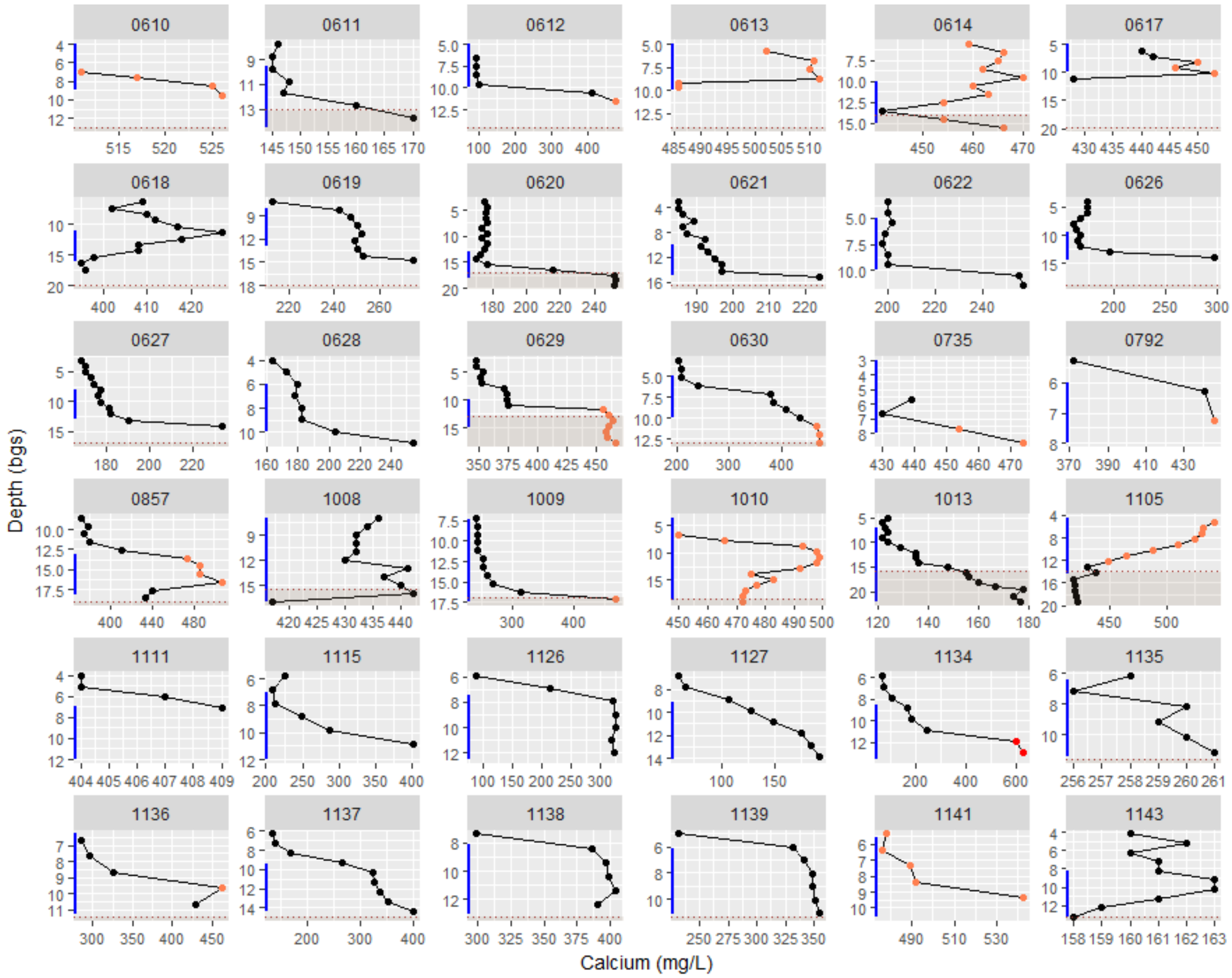
Use of a logarithmic *x*-axis scale may mask the magnitude of change in potassium concentrations with depth.

- casing
- screen
- sump

--- mean potassium concentration in Phase II Shiprock site floodplain data set (32.8 mg/L)

bgs below ground surface

Calcium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

| screened interval

····· bedrock contact

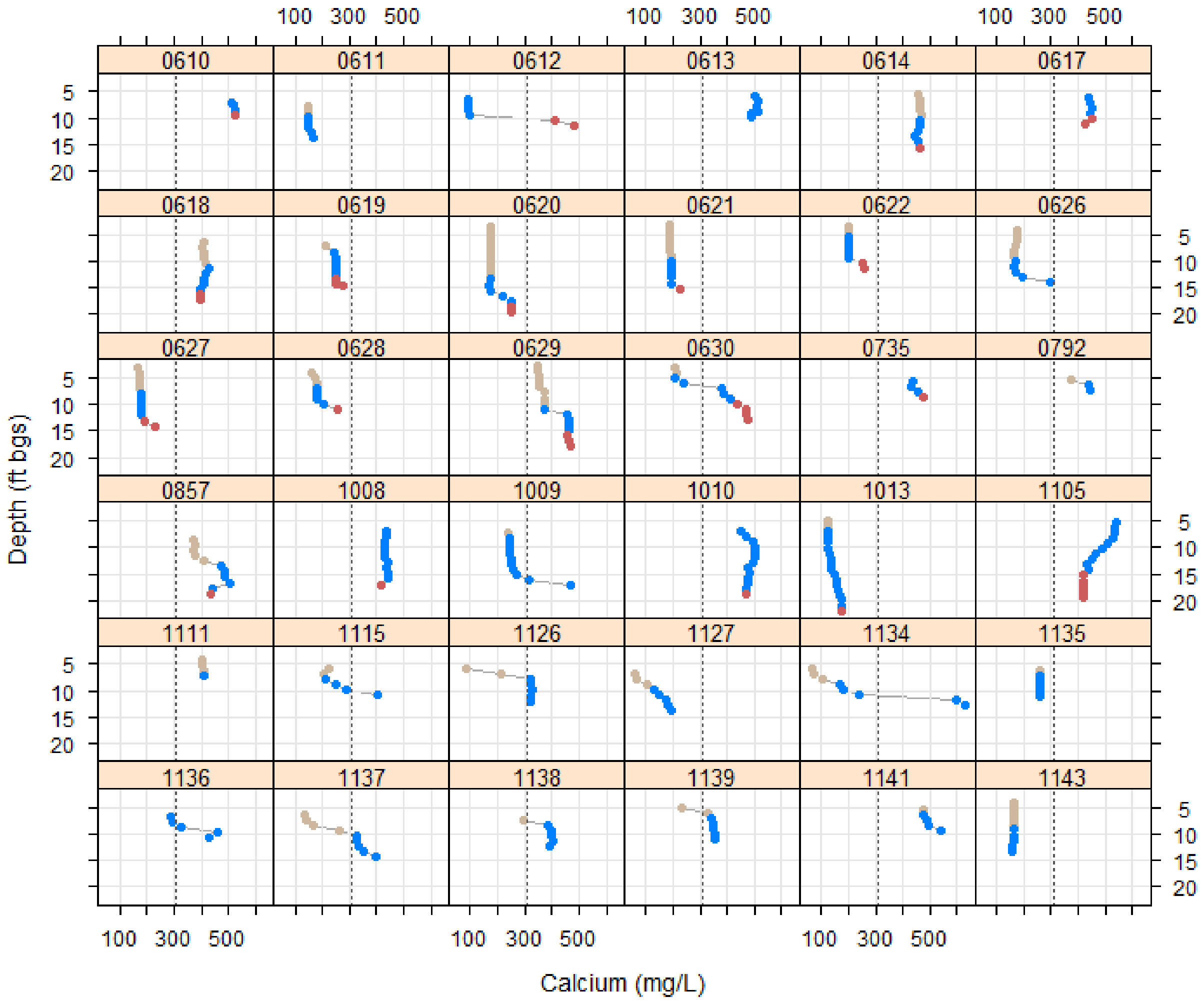
Mancos Shale

bgs below ground surface

To provide a context for interpreting results, points are color-coded based on the distribution of calcium in the Phase II Shiprock site floodplain data set. The mean and standard deviation (SD) were 308 and 135 mg/L, respectively.

- ● calcium ≤ 443 mg/L (mean + 1×SD)
- ● calcium > 443 mg/L (no results exceeded the mean + 2×SD, 578 mg/L)

Calcium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



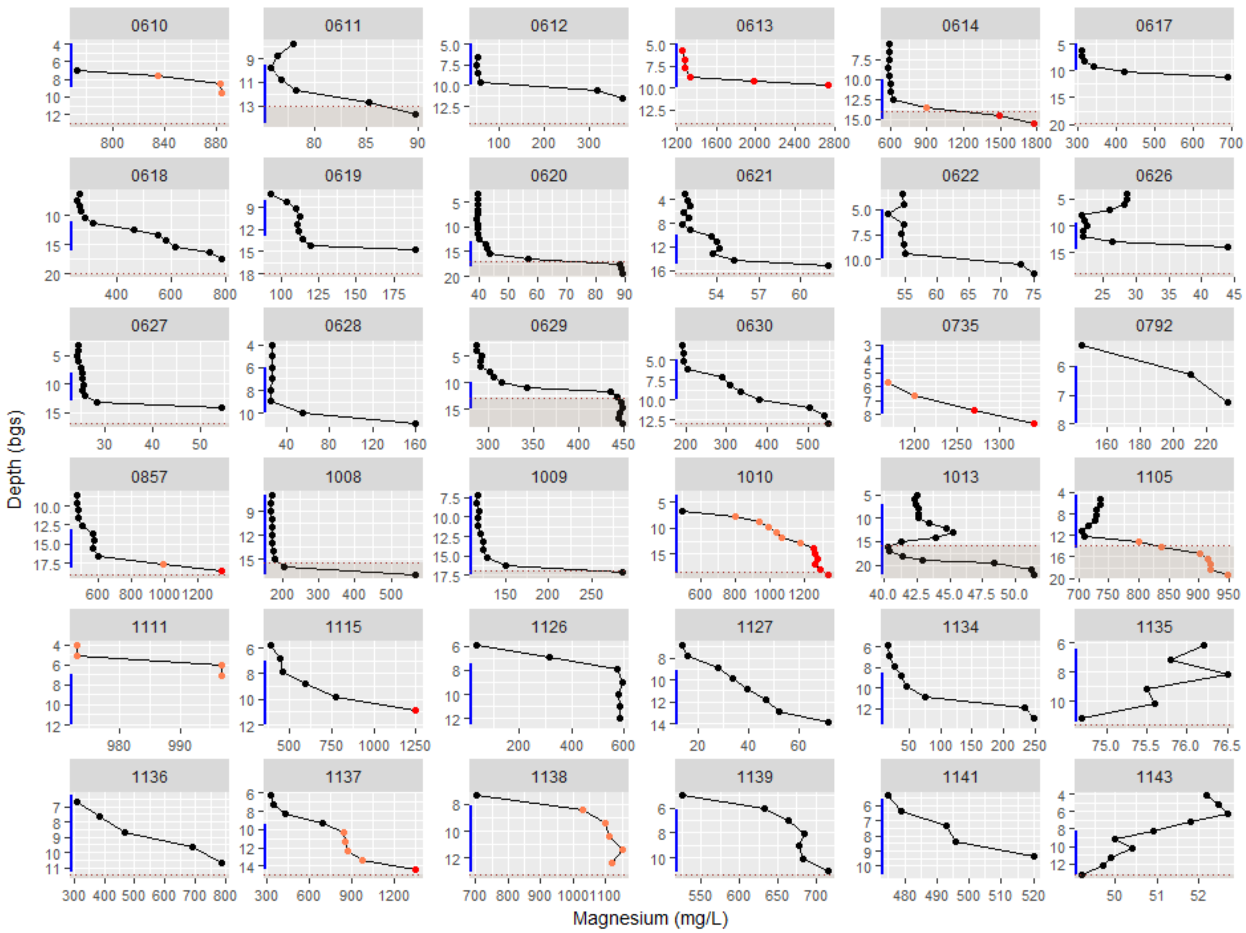
Notes:

- casing
- screen
- sump

--- mean calcium concentration in Phase II Shiprock site floodplain data set (308 mg/L)

bgs below ground surface

Magnesium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

| screened interval

······ bedrock contact

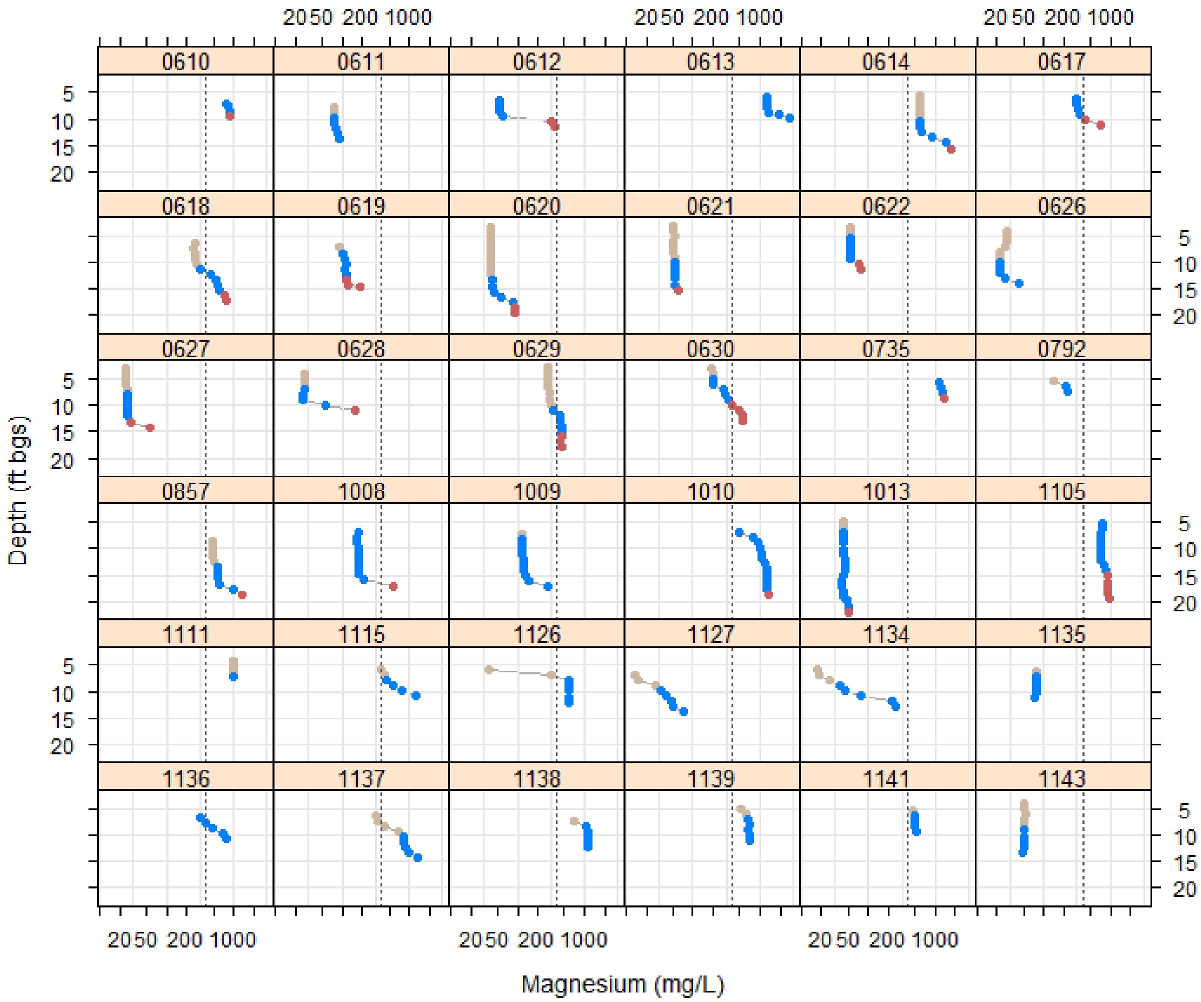
Mancos Shale

bgs below ground surface

To provide a context for interpreting results, points are color-coded based on the distribution of magnesium in the Phase II Shiprock site floodplain data set. The mean and standard deviation (SD) were 382 and 416 mg/L, respectively.

- magnesium ≤ 798 mg/L (mean + 1×SD)
- 798 < magnesium ≤ 1215 mg/L (mean + 2×SD)
- magnesium > 1215 mg/L

Magnesium Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



Notes:

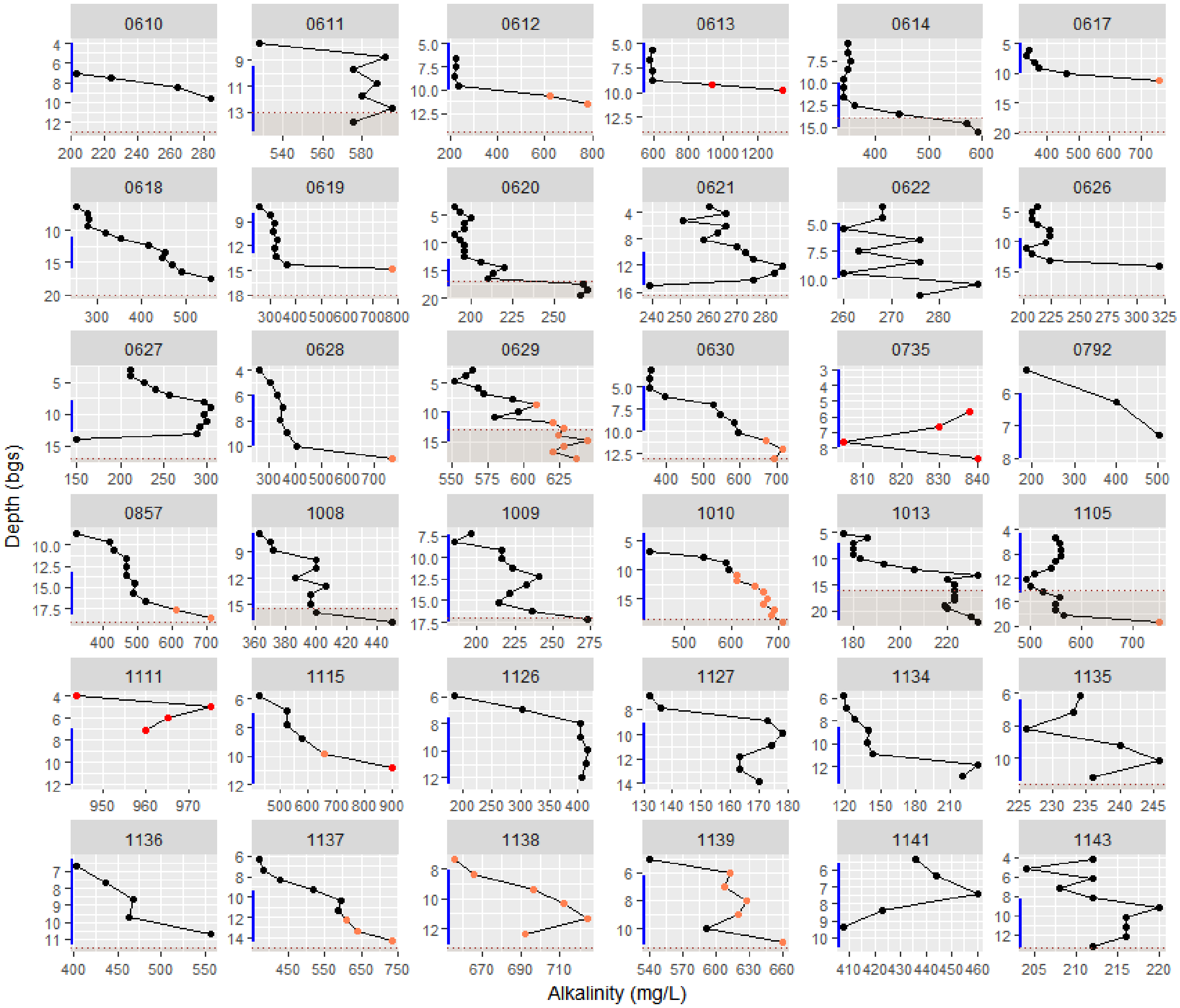
Use of a logarithmic *x*-axis scale may mask the magnitude of change in magnesium concentrations with depth.

- casing
- screen
- sump

--- mean potassium concentration in Phase II Shiprock site floodplain data set (382 mg/L)

bgs below ground surface

Alkalinity(as $CaCO_3$) Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

| screened interval

····· bedrock contact

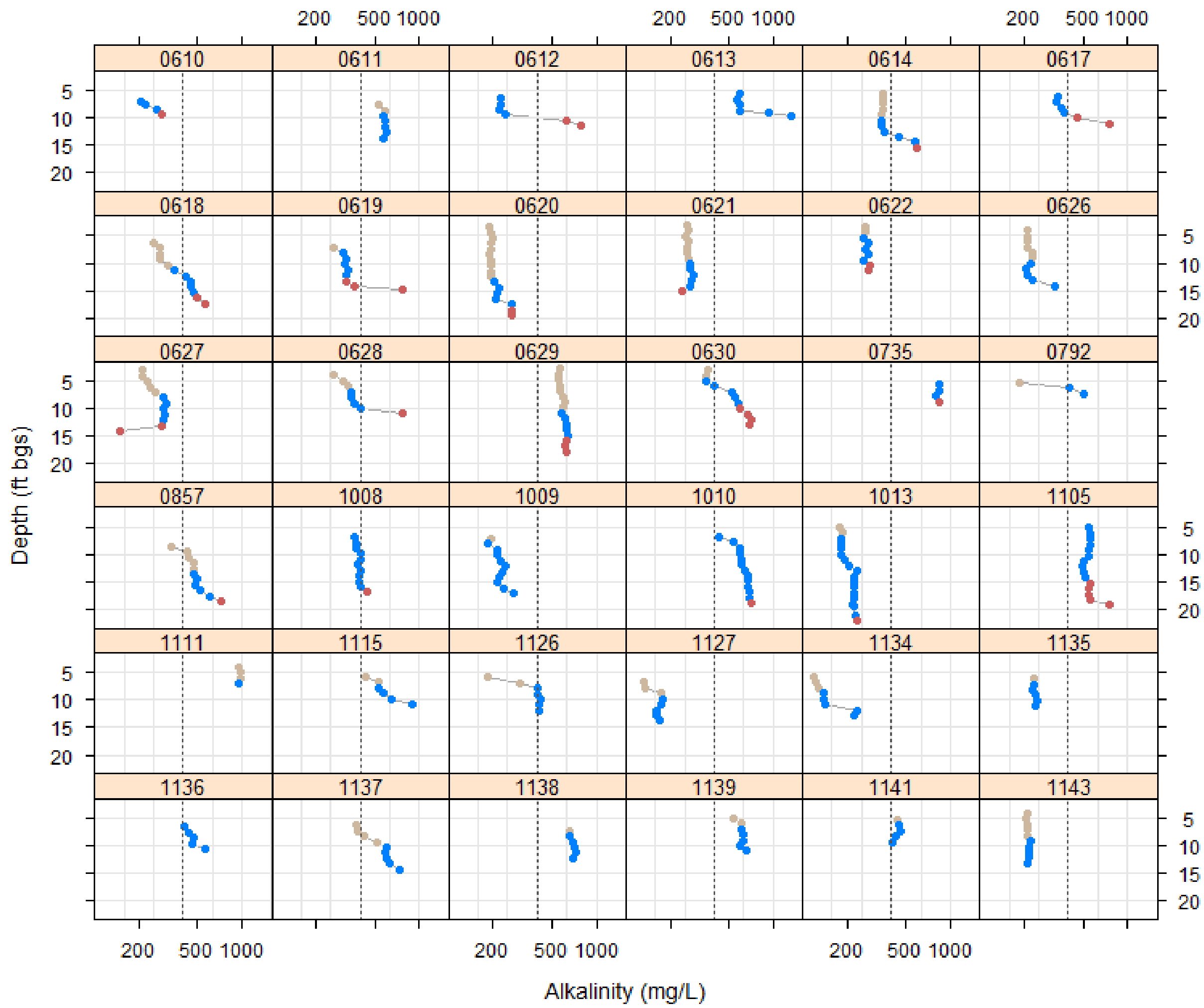
Mancos Shale

bgs below ground surface

To provide a context for interpreting results, points are color-coded based on the distribution of alkalinity in the Phase II Shiprock site floodplain data set. The mean and standard deviation (SD) were 403 and 199 mg/L, respectively (rounded).

- ● alkalinity ≤ 602 mg/L (mean + 1×SD)
- ● 602 < alkalinity ≤ 801 (mean + 2×SD)
- ● alkalinity > 801 (well 0735 only)

Alkalinity (as $CaCO_3$) Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Common Scales



Notes:

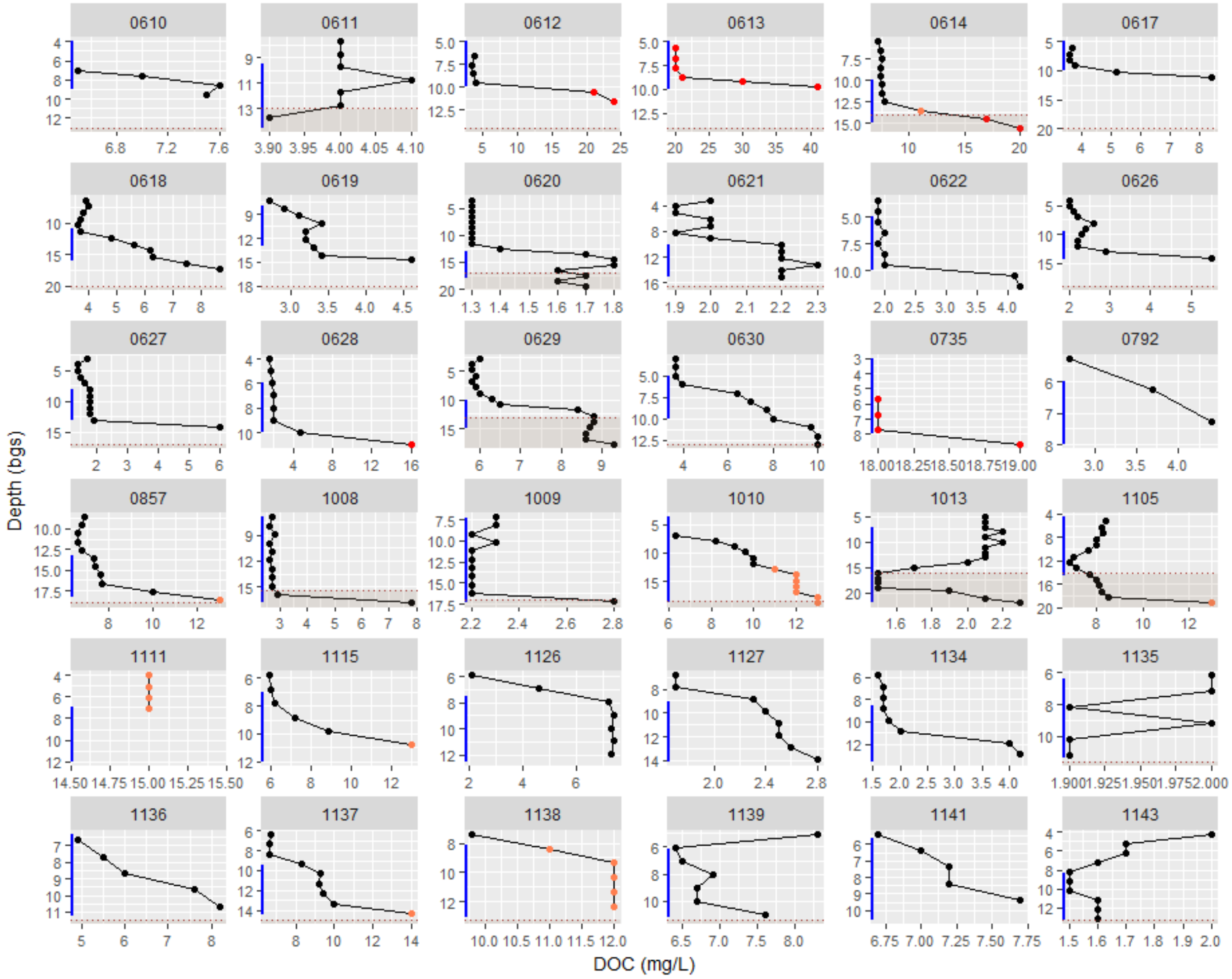
Use of a logarithmic *x*-axis scale may mask the magnitude of change in alkalinity concentrations with depth.

- casing
- screen
- sump

--- mean alkalinity (as $CaCO_3$) concentration in Phase II Shiprock site floodplain data set (403 mg/L)

bgs below ground surface

Dissolved Organic Carbon Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Notes:

| screened interval

······ bedrock contact

Mancos Shale

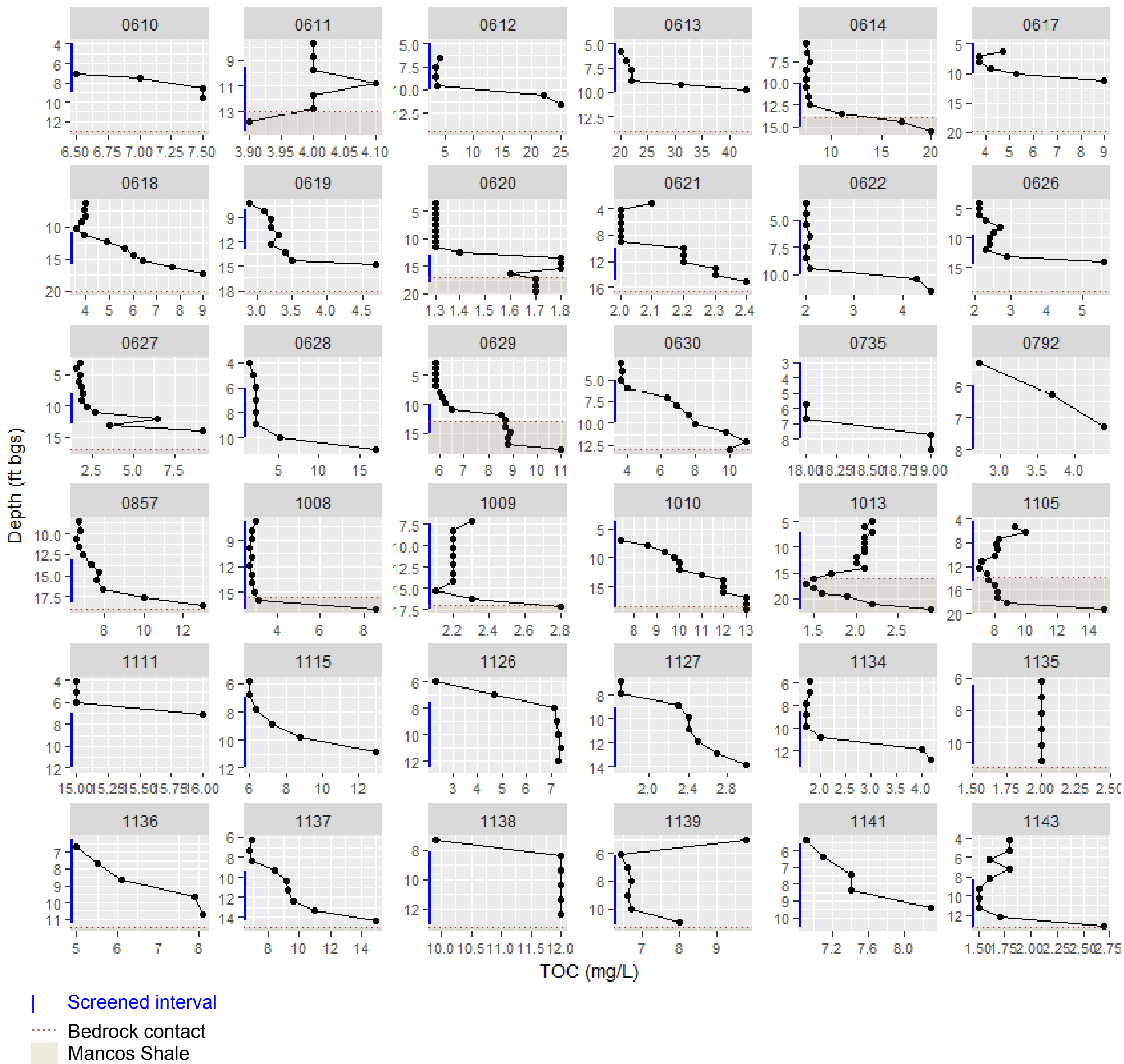
bgs below ground surface

DOC dissolved organic carbon

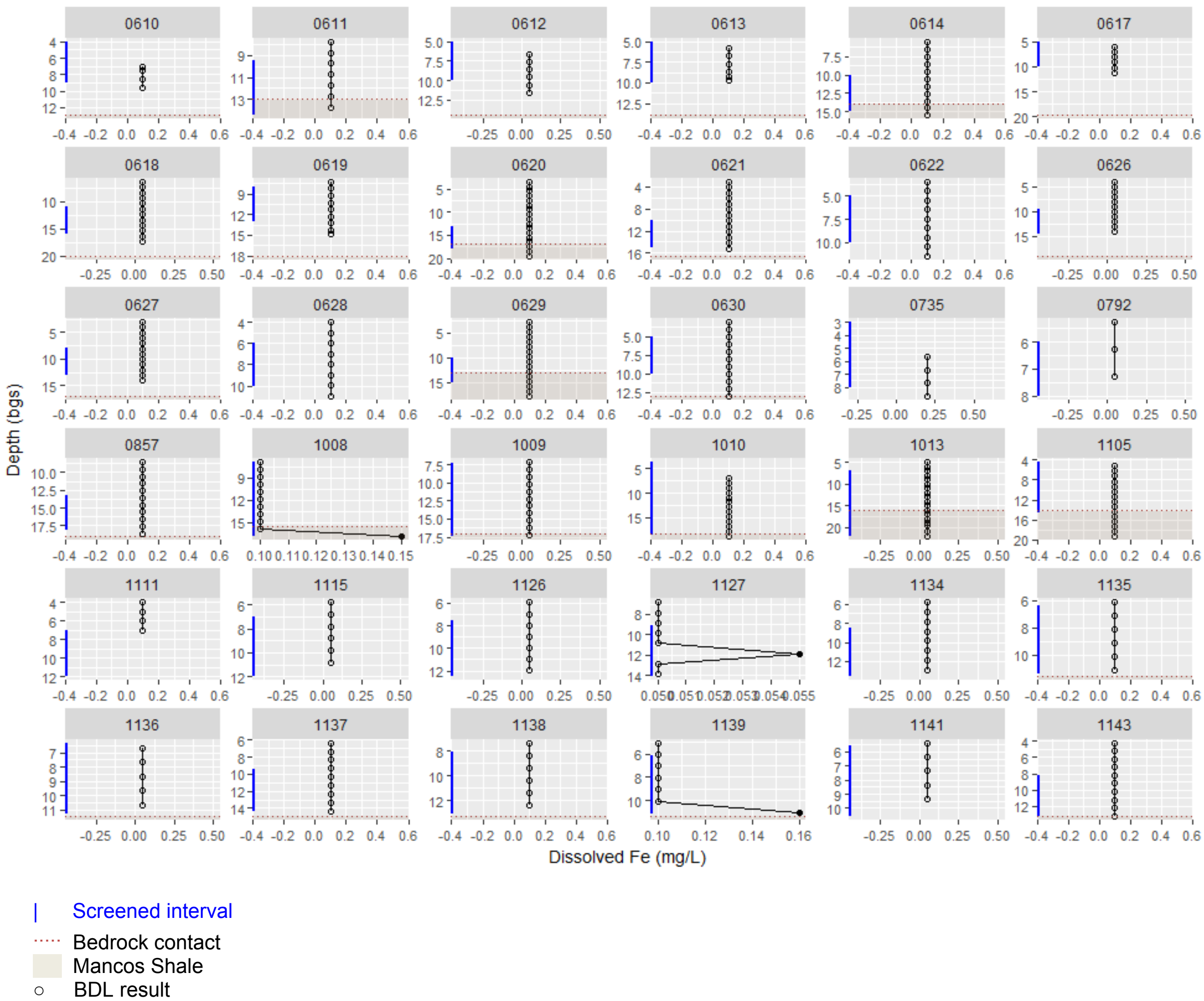
To provide a context for interpreting results, points are color-coded based on the distribution of DOC in the Phase II Shiprock site floodplain data set. The mean and standard deviation (SD) were 5.7 and 5 mg/L, respectively.

- DOC ≤ 10.7 mg/L (mean + 1×SD)
- 10.7 < DOC ≤ 15.6 (mean + 2×SD)
- DOC > 15.6

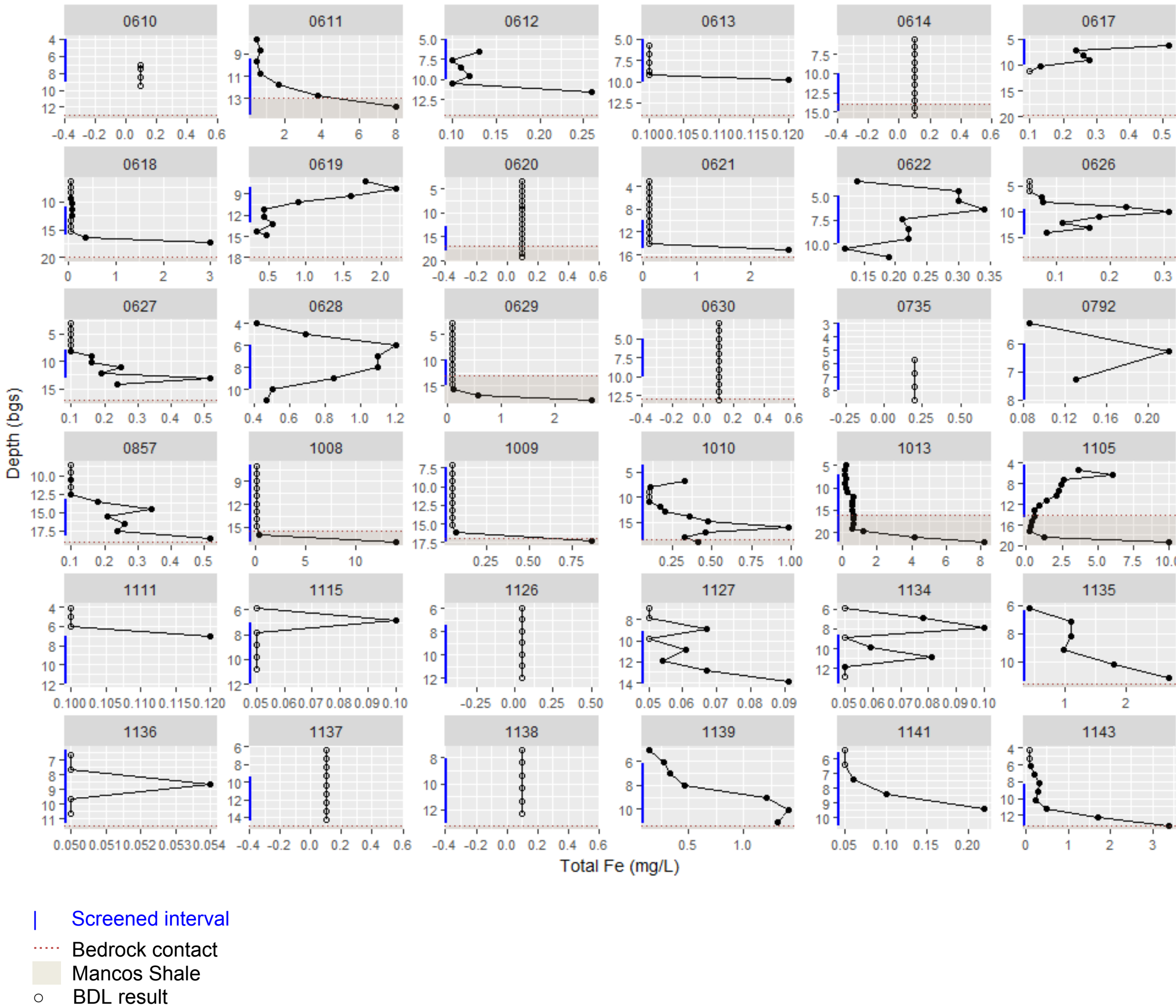
Total Organic Carbon Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



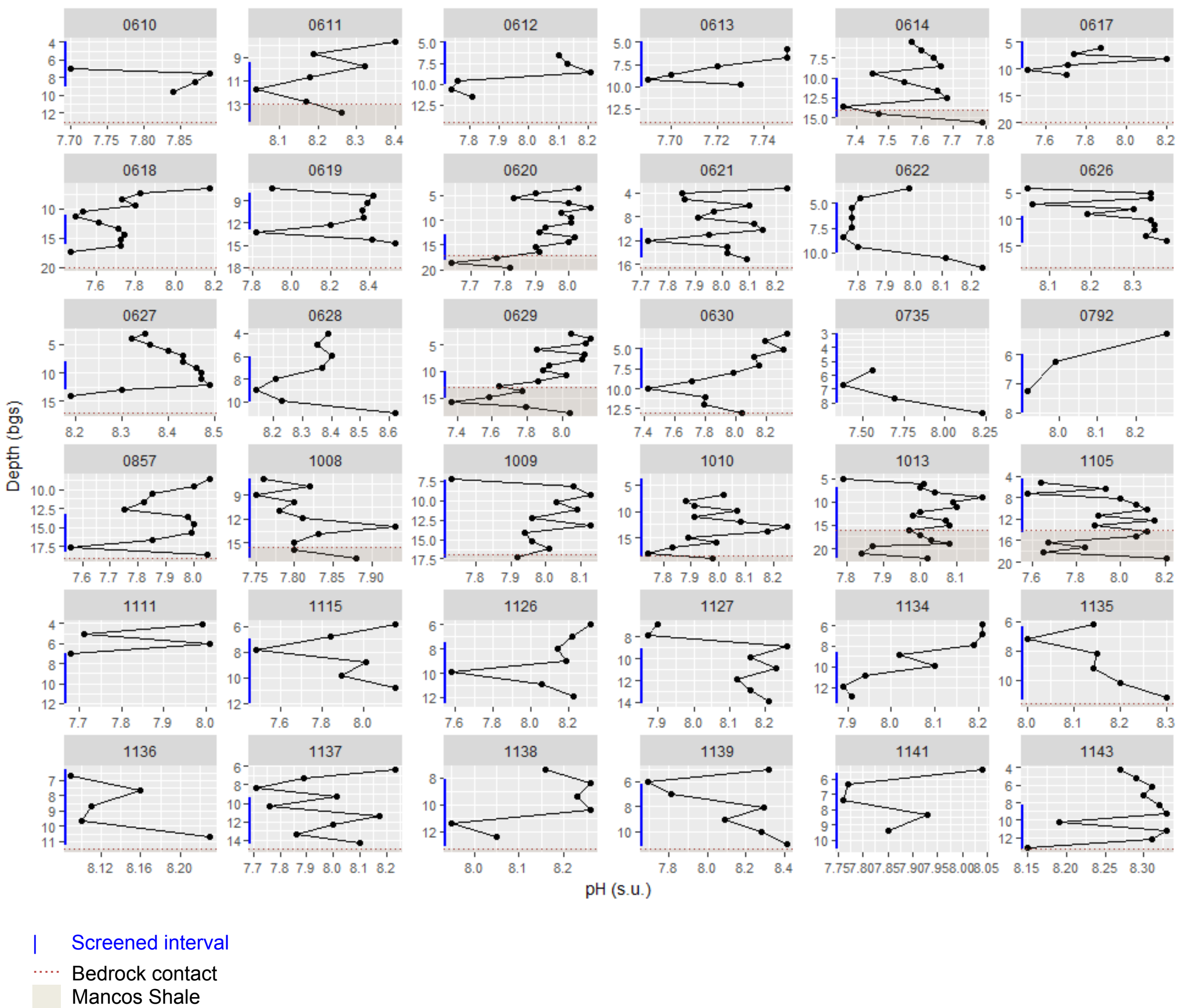
Dissolved Iron Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Total Iron Concentrations by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



pH by Depth in Shiprock Site Floodplain Wells
Phase II Profiles, Unique Scales



Appendix E-2

Vertical Profiles by Well

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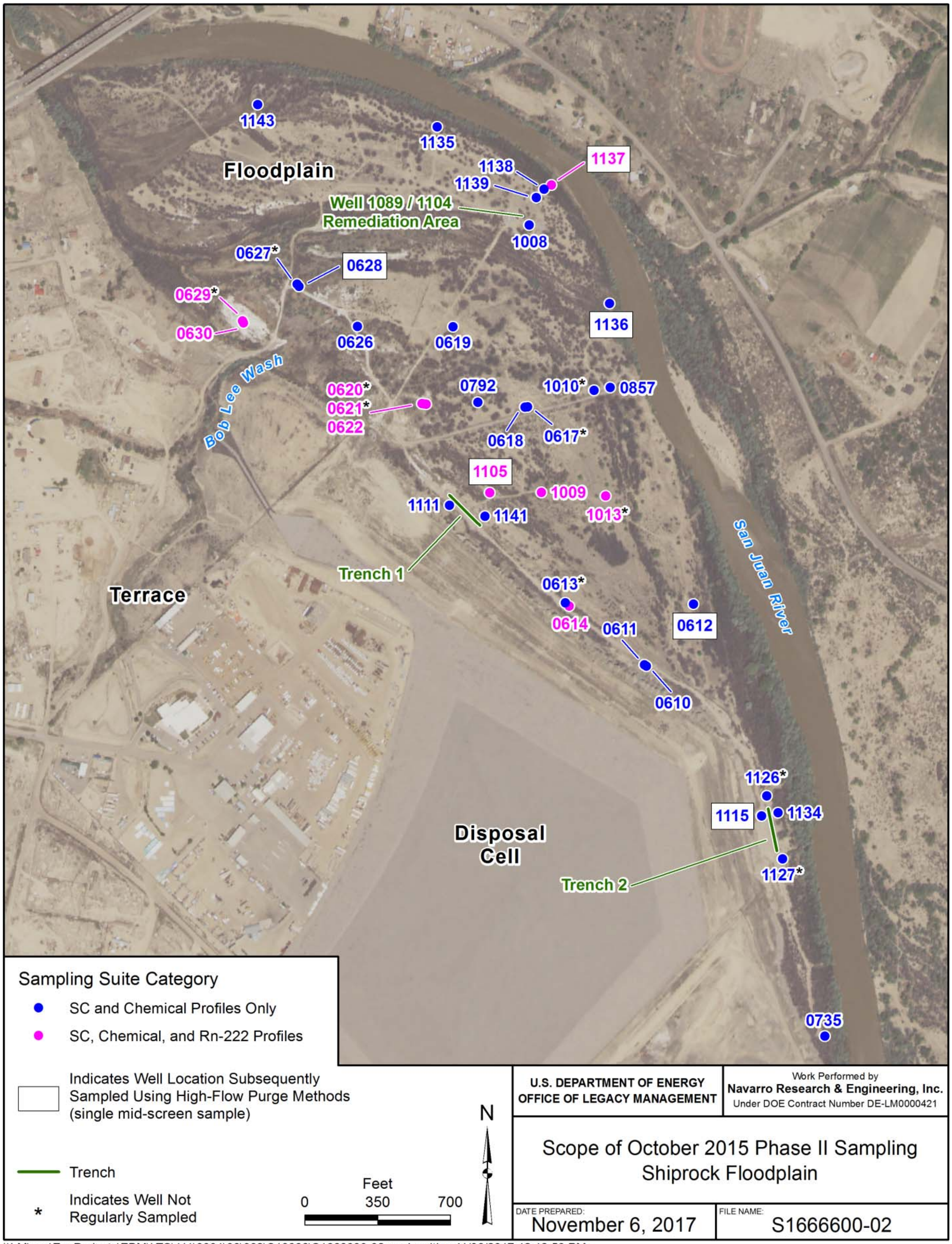


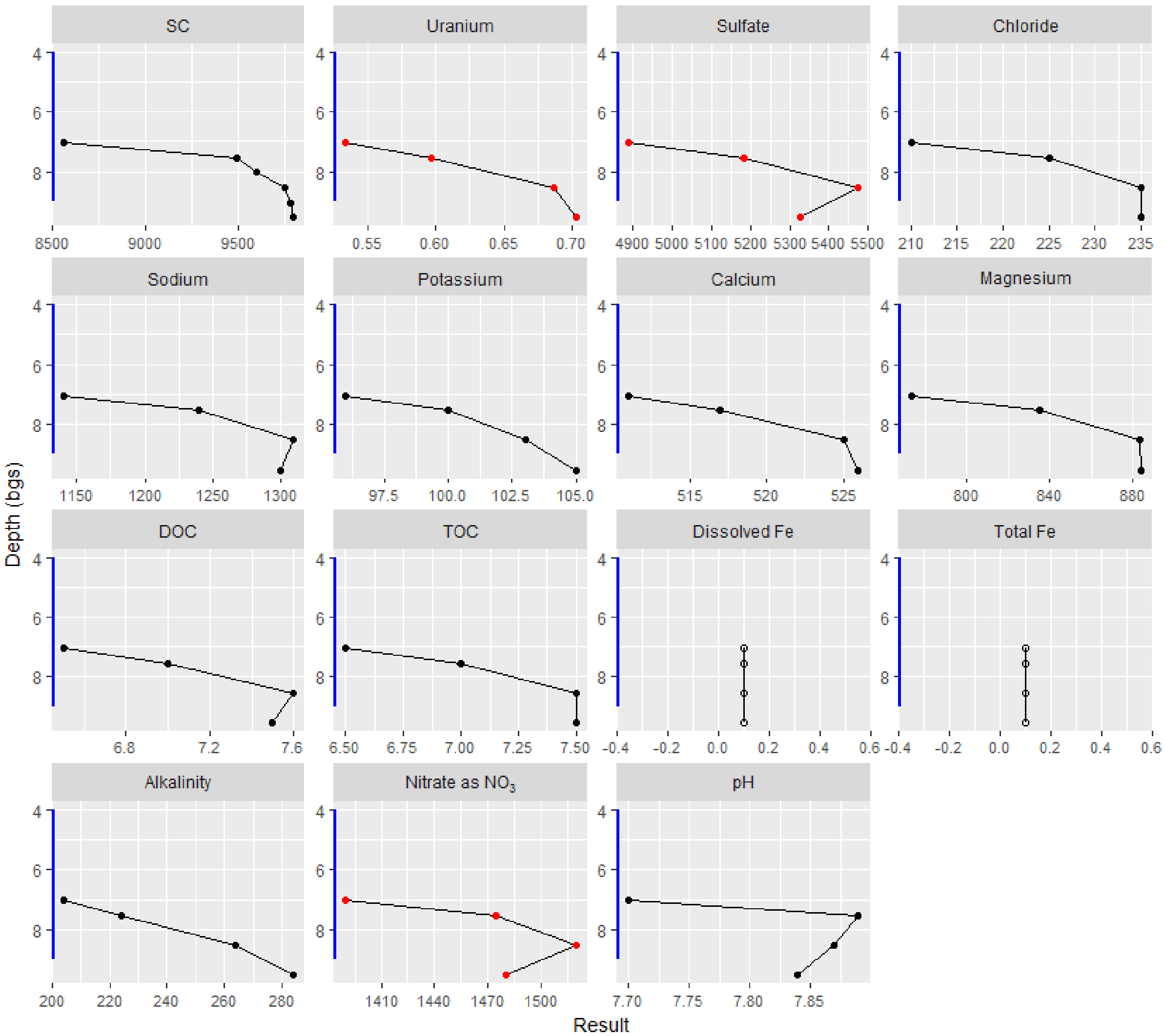
\\LM\ess\EnvProjects\EBM\LTS\111\0001\08\002\S16666\S1666600-02.mxd smithw 11/06/2017 12:12:56 PM

Figure duplicated from Figure 39 of the main text.

Sample Location Map: Shiprock Site Floodplain Wells Profiled in Phase II

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Well 0610



Notes:

| screened interval*

○ Hollow symbol denotes result below detection limit.

● Red symbols denote results exceeding corresponding standard:
0.044 mg/L uranium; 2000 mg/L sulfate; and 44 mg/L nitrate as NO_3

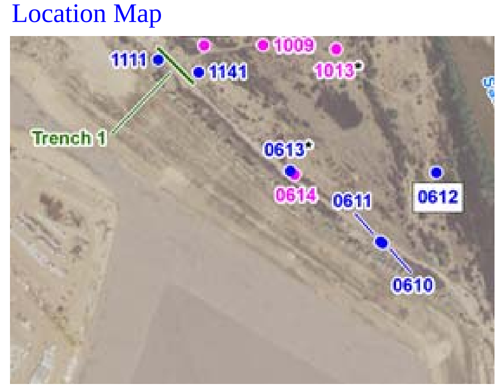
Well location shown in inset to right (adapted from Figure 39 of main text)
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

*The April 2016 downhole video indicated that the screen was about 1 ft higher than the placement indicated in the well log (Appendix B, Table B.2.3). If this is the case, half of the profile measurements were taken from the sump.

Abbreviations

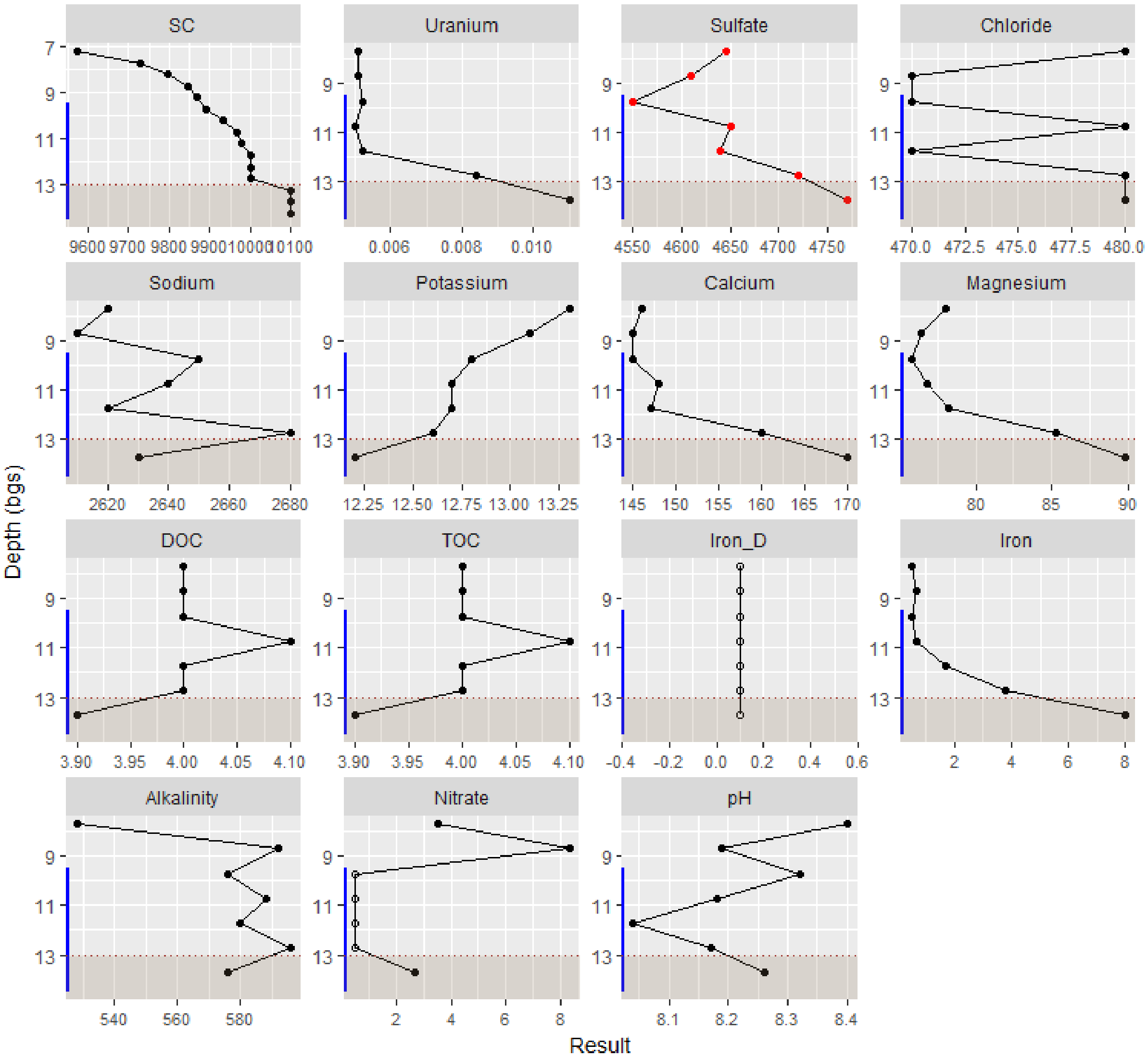
bgs	below ground surface
DOC	dissolved organic carbon
Fe	iron
SC	specific conductance
TOC	total organic carbon

Location Map



Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Well 0611



Notes:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

| screened interval*

····· bedrock contact; Mancos Shale

● Red symbols denote results exceeding corresponding standard: 0.044 mg/L uranium; 2000 mg/L sulfate; and 44 mg/L nitrate as NO_3

○ Hollow symbol denotes result below detection limit.

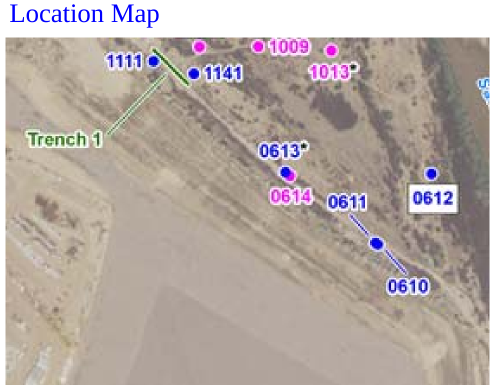
Well location shown in inset to right (adapted from Figure 39 of main text)

*The April 2016 downhole video indicated that the screen was about 1.5 ft higher than the placement indicated in the well log (refer to Appendix B, Table B.2.3).

Abbreviations

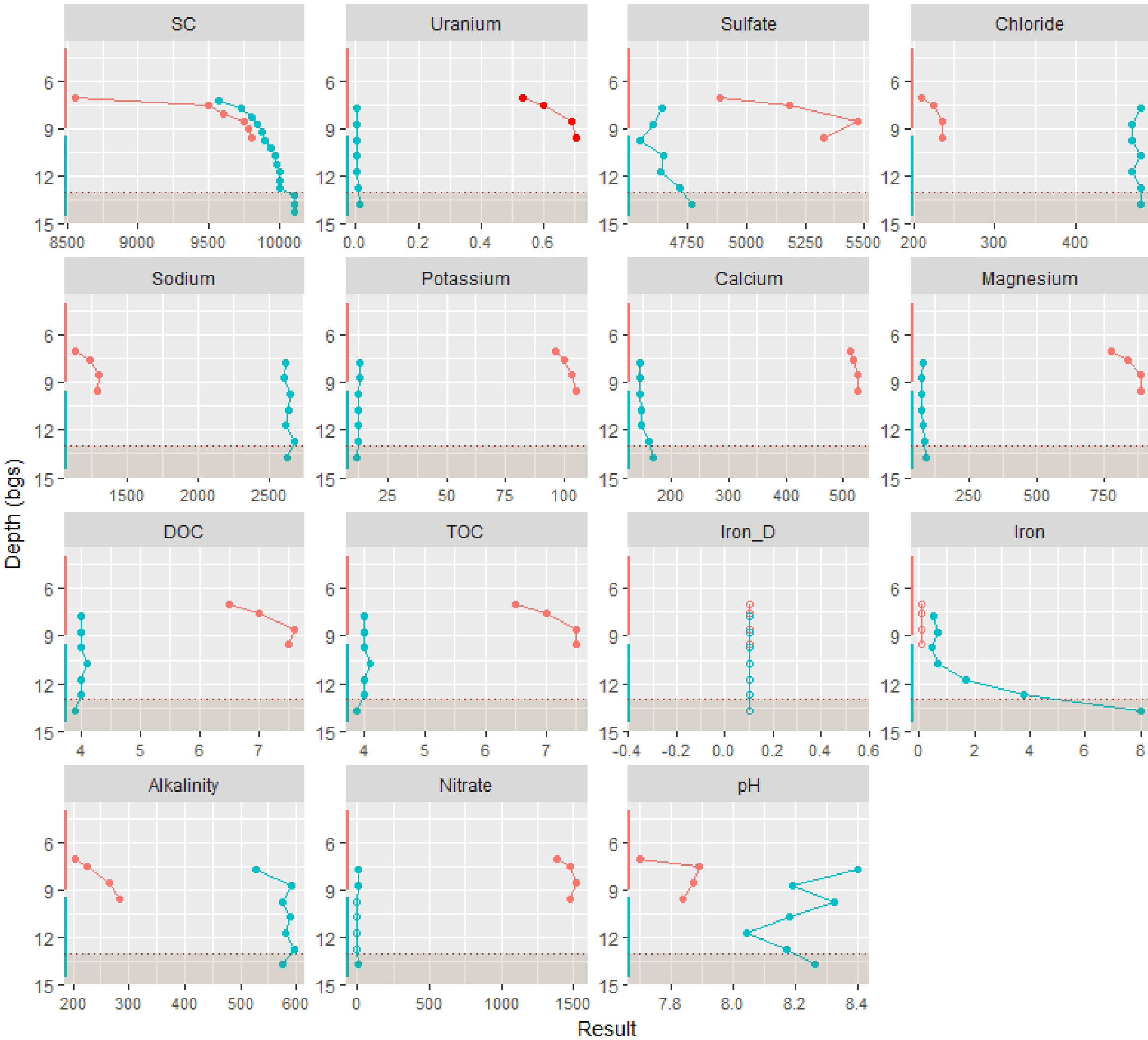
bgs below ground surface
DOC dissolved organic carbon
Iron_D dissolved iron (followed by total iron)
SC specific conductance
TOC total organic carbon

Location Map



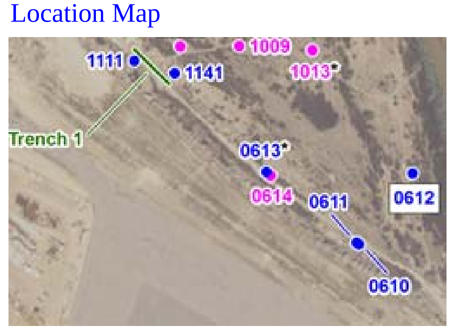
Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Colocated Well Pair 0610 (orange) and 0611 (blue)



bgs below ground surface
Fe iron
SC specific conductance
| Well screens shown to left of each plot
····· bedrock contact; Mancos Shale
○ Hollow symbol denotes result below detection limit.

Location Map



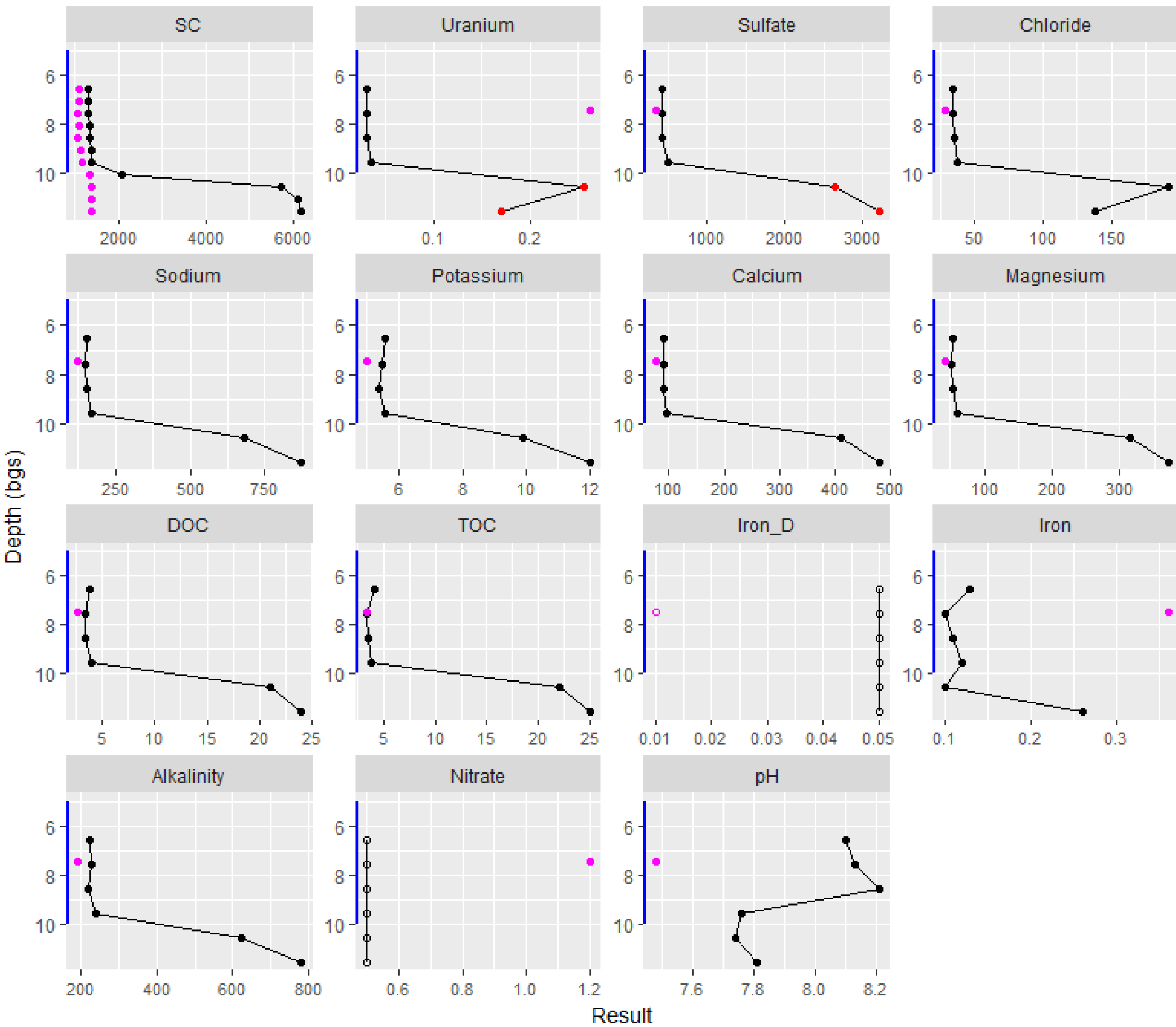
Notes:

Well locations shown in inset to right (adapted from Figure 39 of main text)
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

*The April 2016 downhole videos suggested that screens in both wells are higher than the placement indicated in the corresponding well logs (Appendix B, Table B.2.3).

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Well 0612



Notes:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$ and nitrate as NO_3.

| screened interval

● vertical profile results using low-flow sampling methods

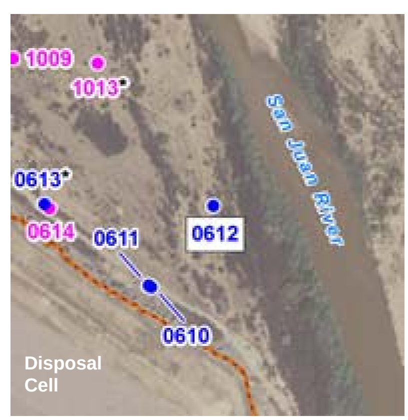
● Red symbols denote results exceeding corresponding standard or background level: 0.044 mg/L uranium; 2000 mg/L sulfate (background); and 44 mg/L nitrate as NO_3

● SC measurement or mid-screen sample result after high-volume purging of well

○ result below detection limit

Well location shown in inset to right (adapted from Figure 39 of main text)

Location Map

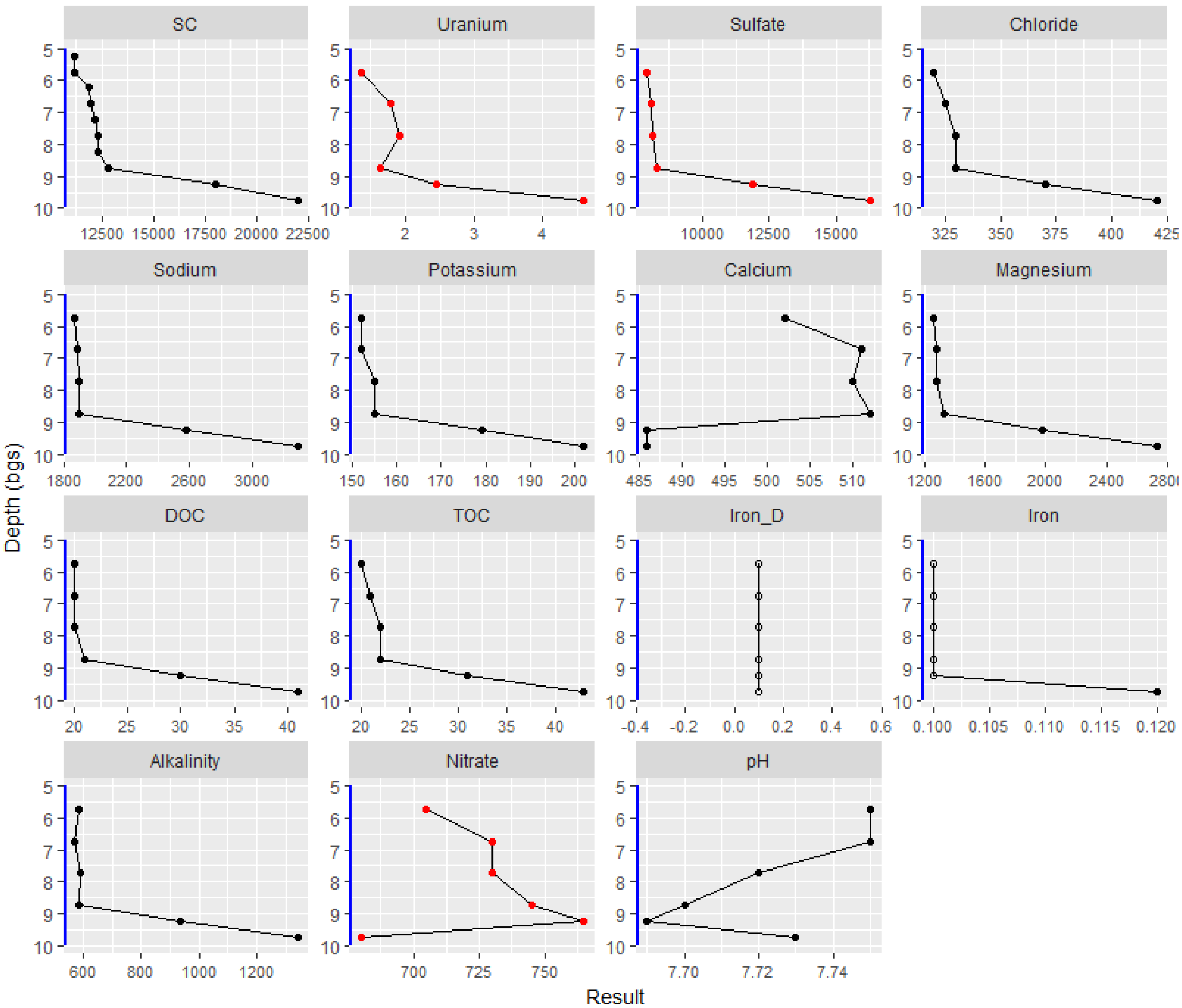


Abbreviations

bgs	below ground surface
DOC	dissolved organic carbon
Iron_D	iron
SC	specific conductance
TOC	total organic carbon

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Well 0613



Notes:

All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$ and nitrate as NO_3.

| screened interval

● Red symbols denote results exceeding corresponding standard or background level: 0.044 mg/L uranium; 2000 mg/L sulfate; and 44 mg/L nitrate as NO_3

○ result below detection limit

Well location shown in inset to right (adapted from Figure 39 of main text)

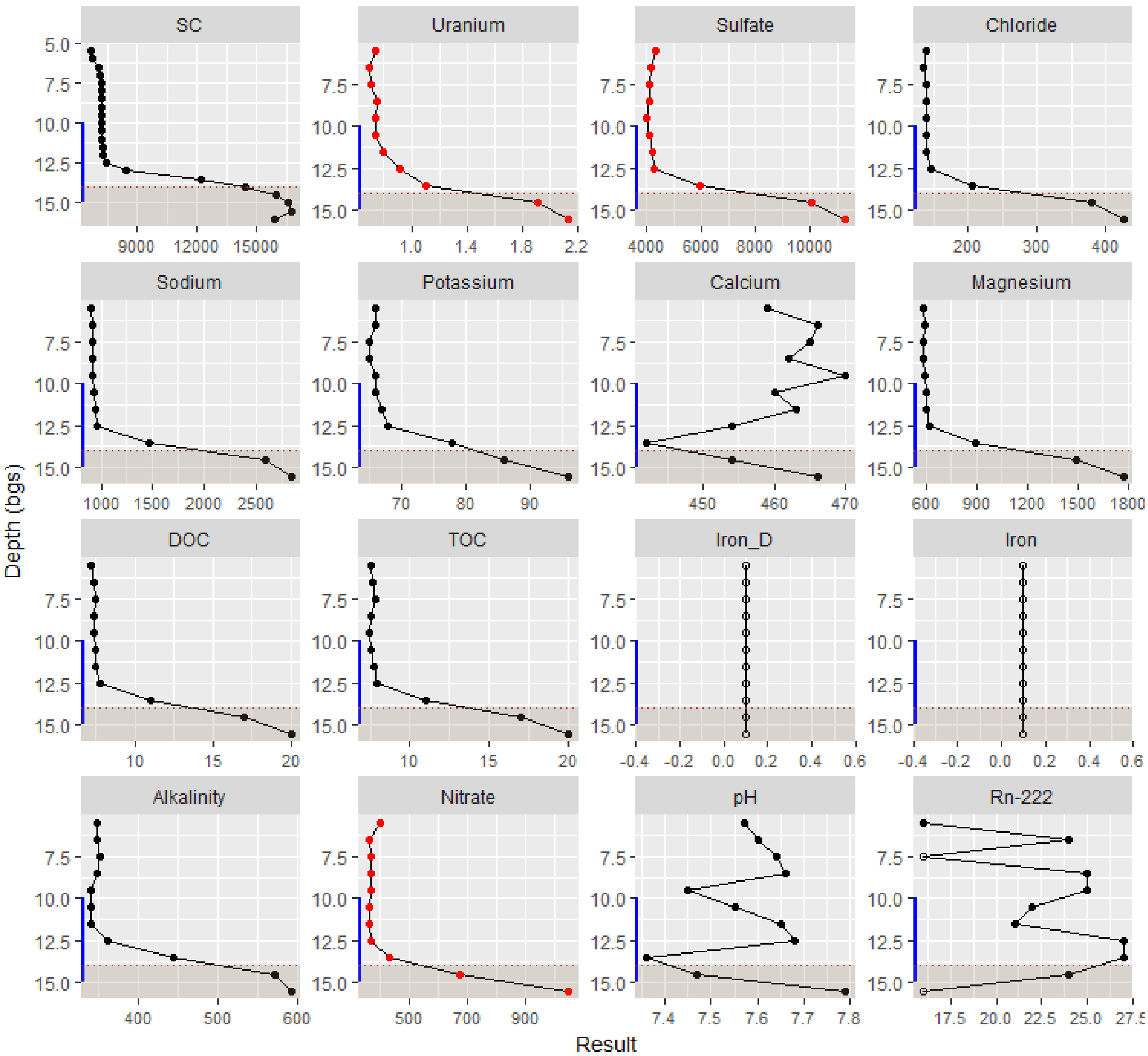
Location Map

Abbreviations

bgs	below ground surface
DOC	dissolved organic carbon
Iron_D	iron
SC	specific conductance
TOC	total organic carbon

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Well 0614



Notes:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$ and nitrate as NO_3.

| screened interval

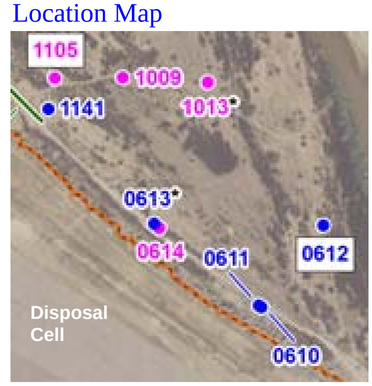
······ bedrock contact   Mancos Shale

● Red symbols denote results exceeding corresponding standard or background level: 0.044 mg/L uranium; 2000 mg/L sulfate; and 44 mg/L nitrate as NO_3

○ result below detection limit

Well location shown in inset to right (adapted from Figure 39 of main text)

Location Map

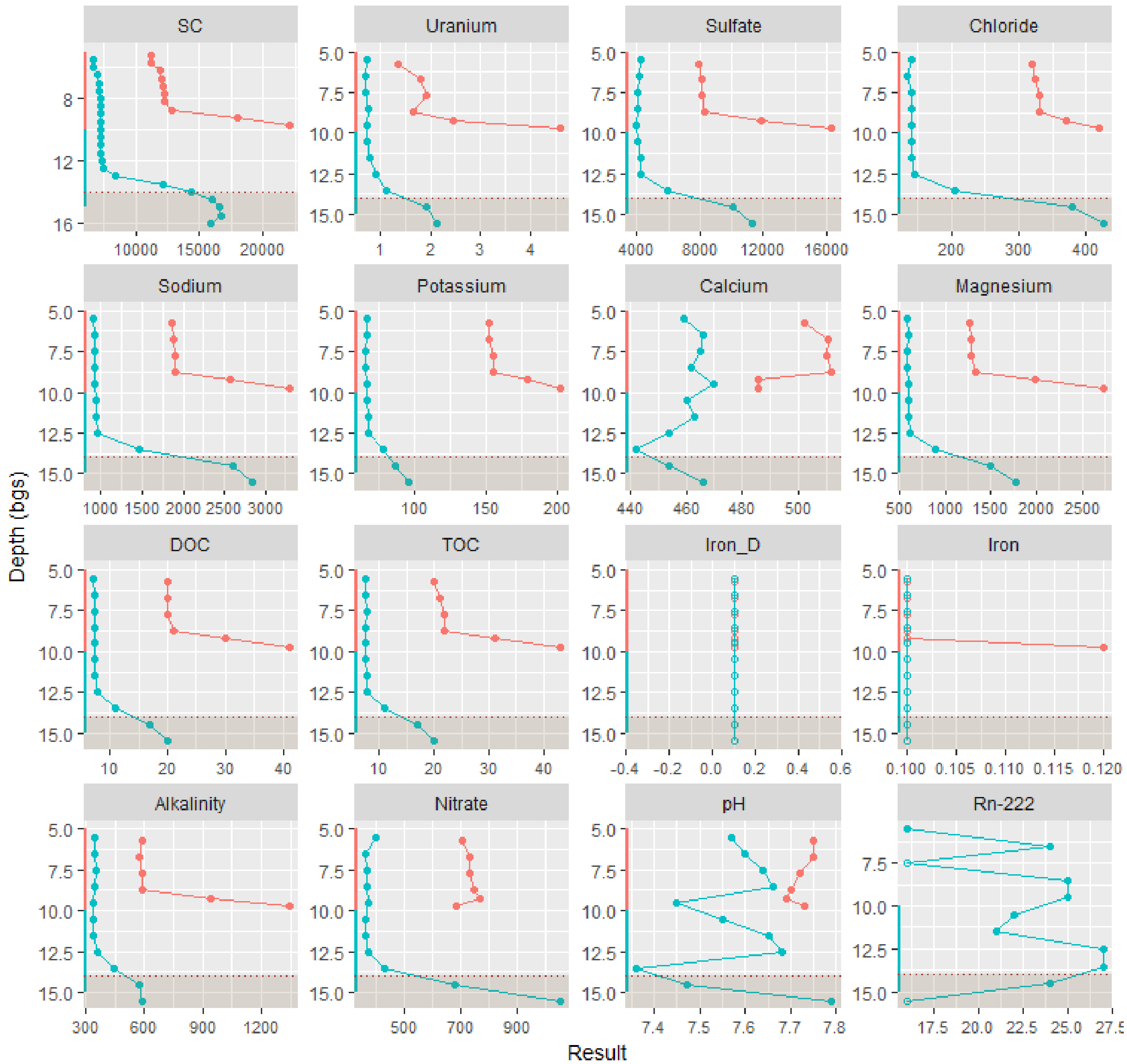


Abbreviations

bgs below ground surface
DOC dissolved organic carbon
Iron_D iron
Rn-222 radon-222
SC specific conductance
TOC total organic carbon

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Colocated Well Pair 0613 (orange) and 0614 (blue)



Notes:

All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$ and nitrate as NO_3.

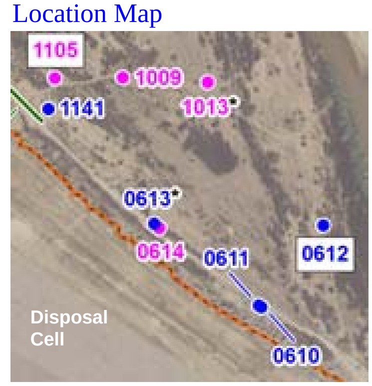
| screened interval

⋯⋯ bedrock contact   Mancos Shale

○ result below detection limit

Well location shown in inset to right (adapted from Figure 39 of main text)

Location Map

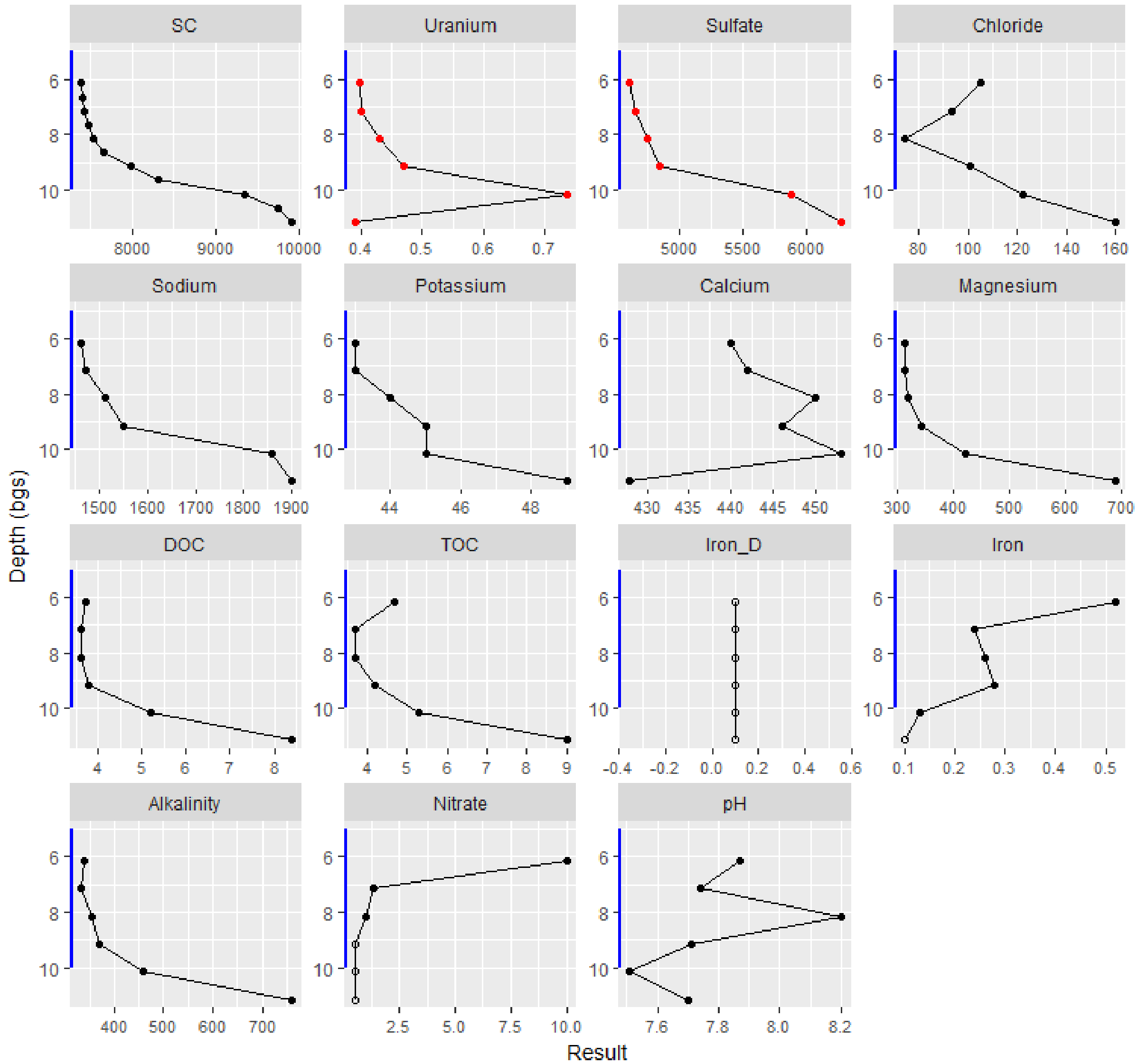


Abbreviations

bgs below ground surface
DOC dissolved organic carbon
Iron_D iron
Rn-222 radon-222
SC specific conductance
TOC total organic carbon

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 0617



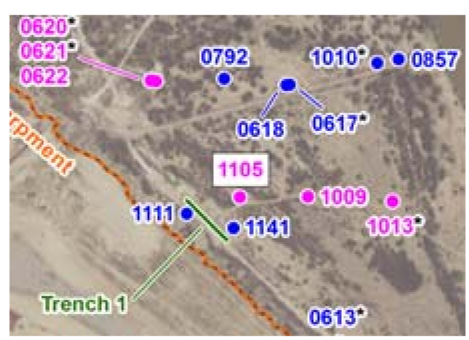
Notes:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

- | screened interval
- ○ below detection limit
- ● result exceeds corresponding 40 CFR 192 MCL or site standard
  - 0.044 mg/L uranium
  - 2000 mg/L sulfate
  - 44 mg/L nitrate as NO_3

Well location shown in inset to right (adapted from Figure 39 of main text)

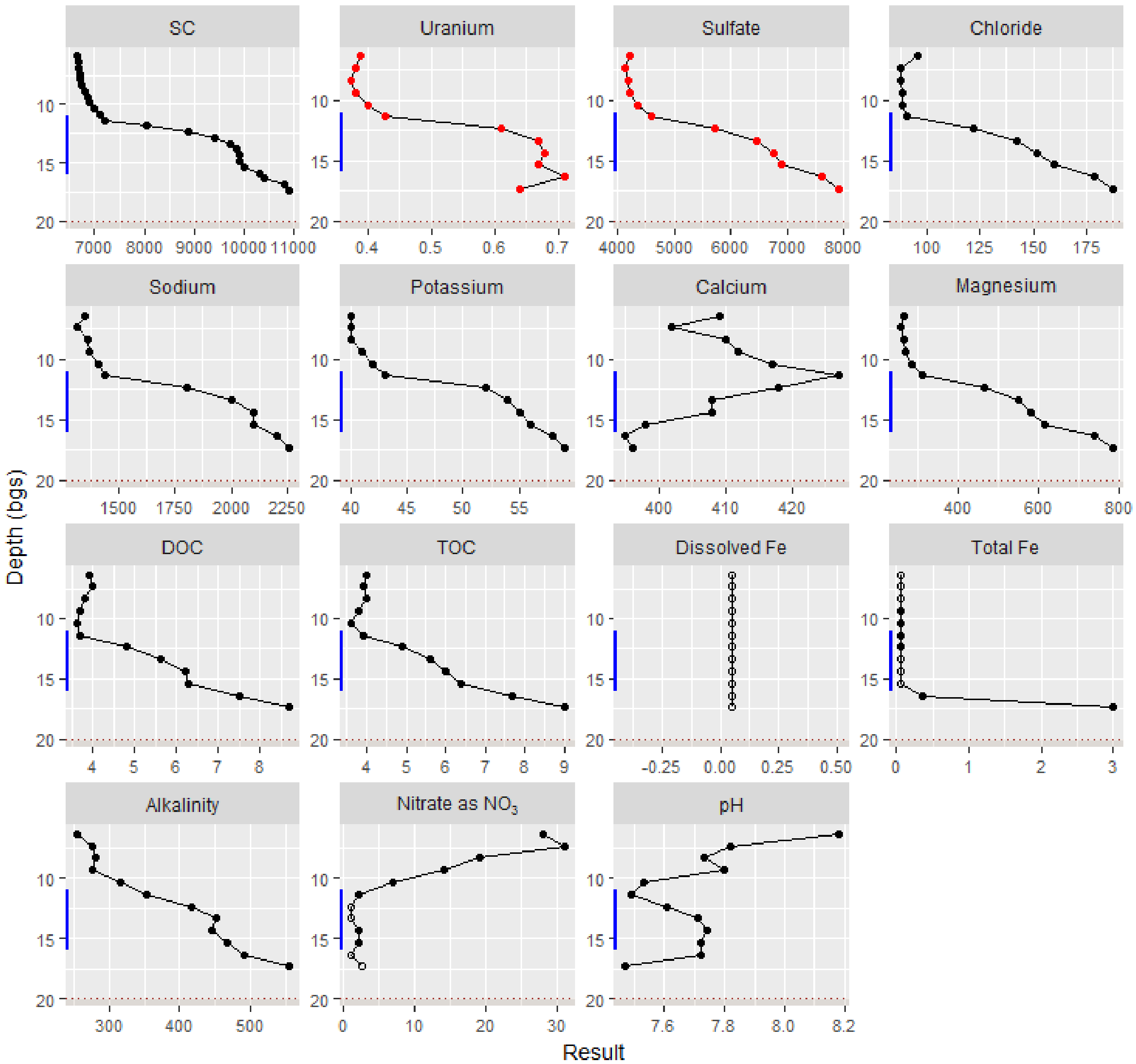
Location Map



Abbreviations:

bgs	below ground surface
DOC	dissolved and total organic carbon
Iron_D	dissolved iron (followed by total iron)
SC	specific conductance
TOC	total organic carbon

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 0618



Notes:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

| screened interval

···· bedrock contact   Mancos Shale

○ below detection limit

● result exceeds corresponding 40 CFR 192 MCL or site standard

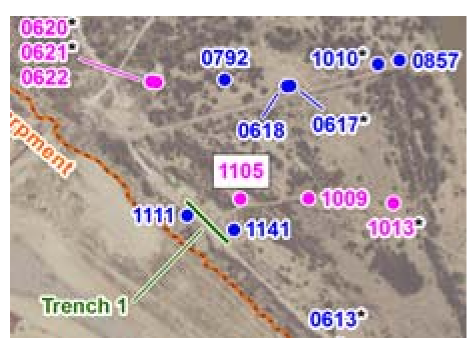
- 0.044 mg/L uranium
- 2000 mg/L sulfate
- 44 mg/L nitrate as NO_3

Well location shown in inset to right (adapted from Figure 39 of main text)

Abbreviations:

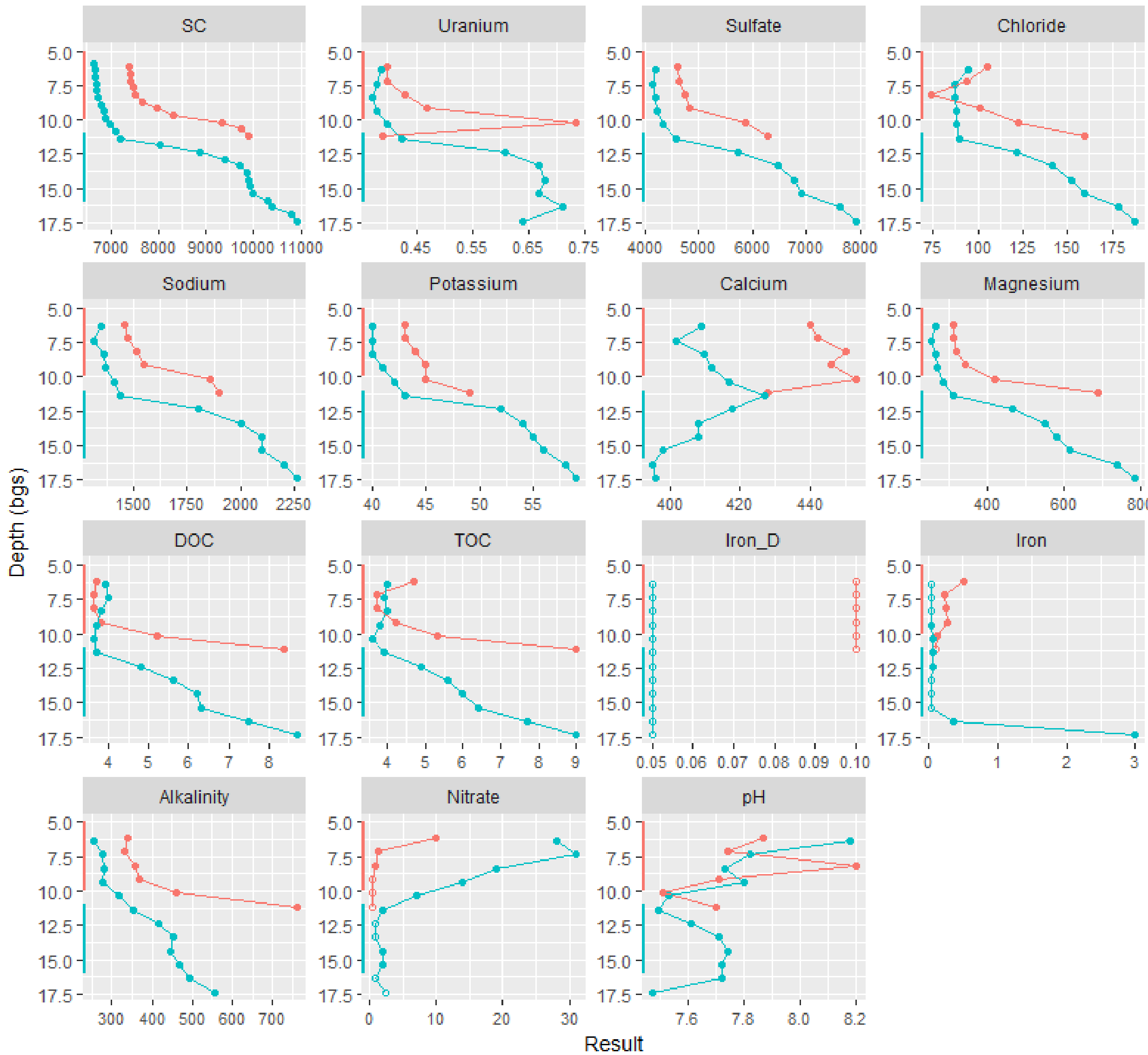
bgs below ground surface
DOC
Fe iron
SC specific conductance
TOC dissolved and total organic carbon

Location Map



Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Colocated Well Pair 0617 (orange) and 0618 (blue)



Notes:

All units in mg/L except SC (µS/cm) and pH ; alkalinity as $CaCO_3$.

| screened interval

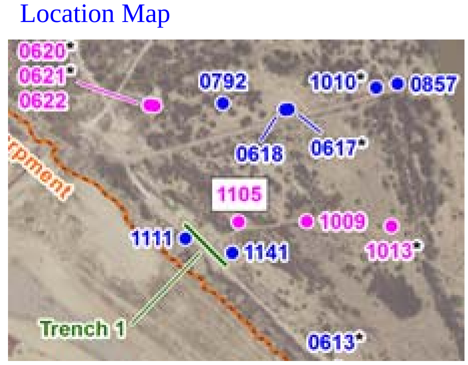
○ below detection limit

Well location shown in inset to right (adapted from Figure 39 of main text)

Abbreviations:

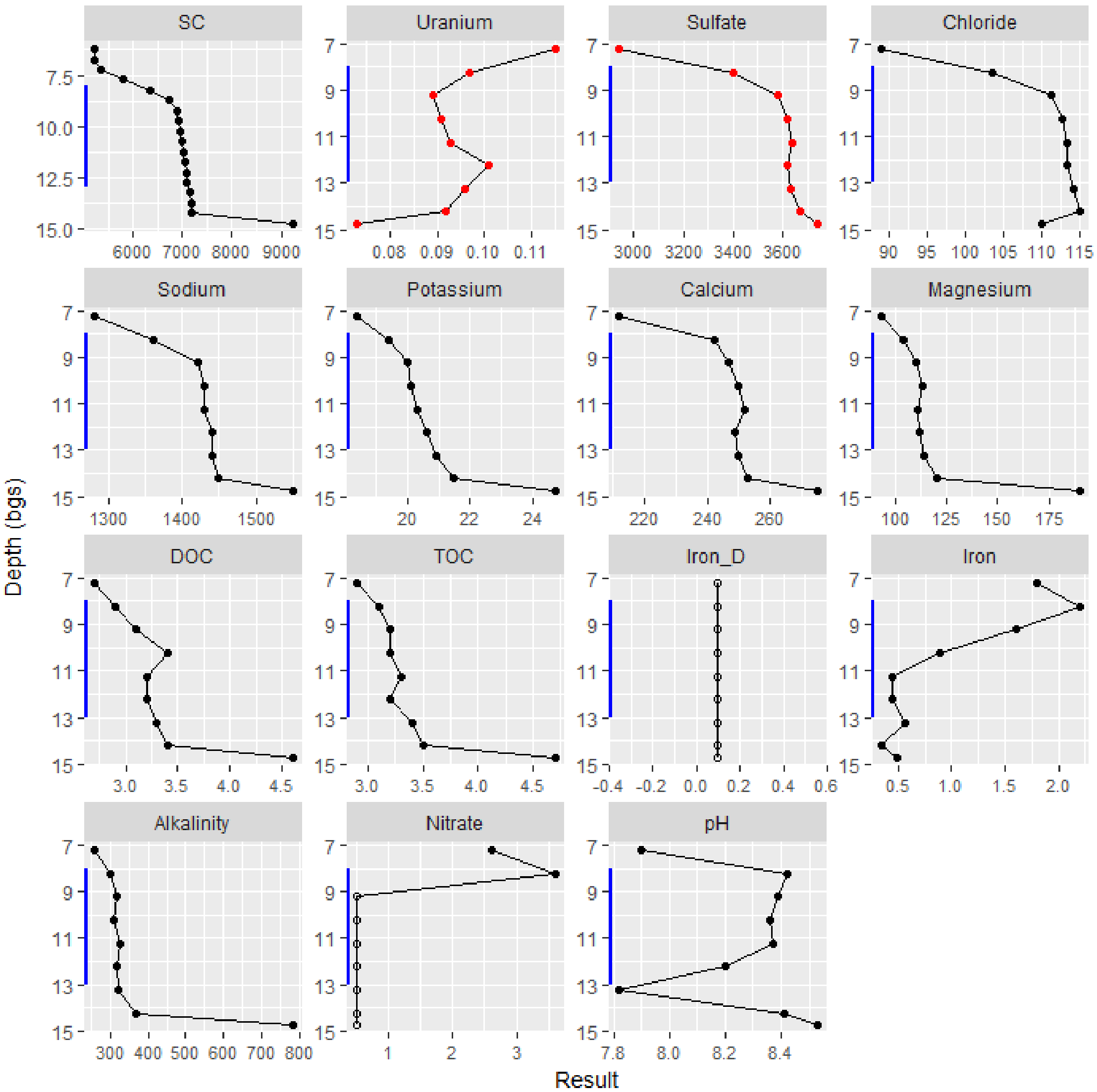
- bgs below ground surface
- DOC dissolved and total organic carbon
- Iron_D dissolved iron (followed by total iron)
- SC specific conductance
- TOC total organic carbon

Location Map



Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 0619



Notes:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

| screened interval

···· bedrock contact Mancos Shale

○ below detection limit

● result exceeds corresponding 40 CFR 192 MCL or site standard

- 0.044 mg/L uranium
- 2000 mg/L sulfate
- 44 mg/L nitrate as NO_3

Well location shown in inset to right (adapted from Figure 39 of main text)

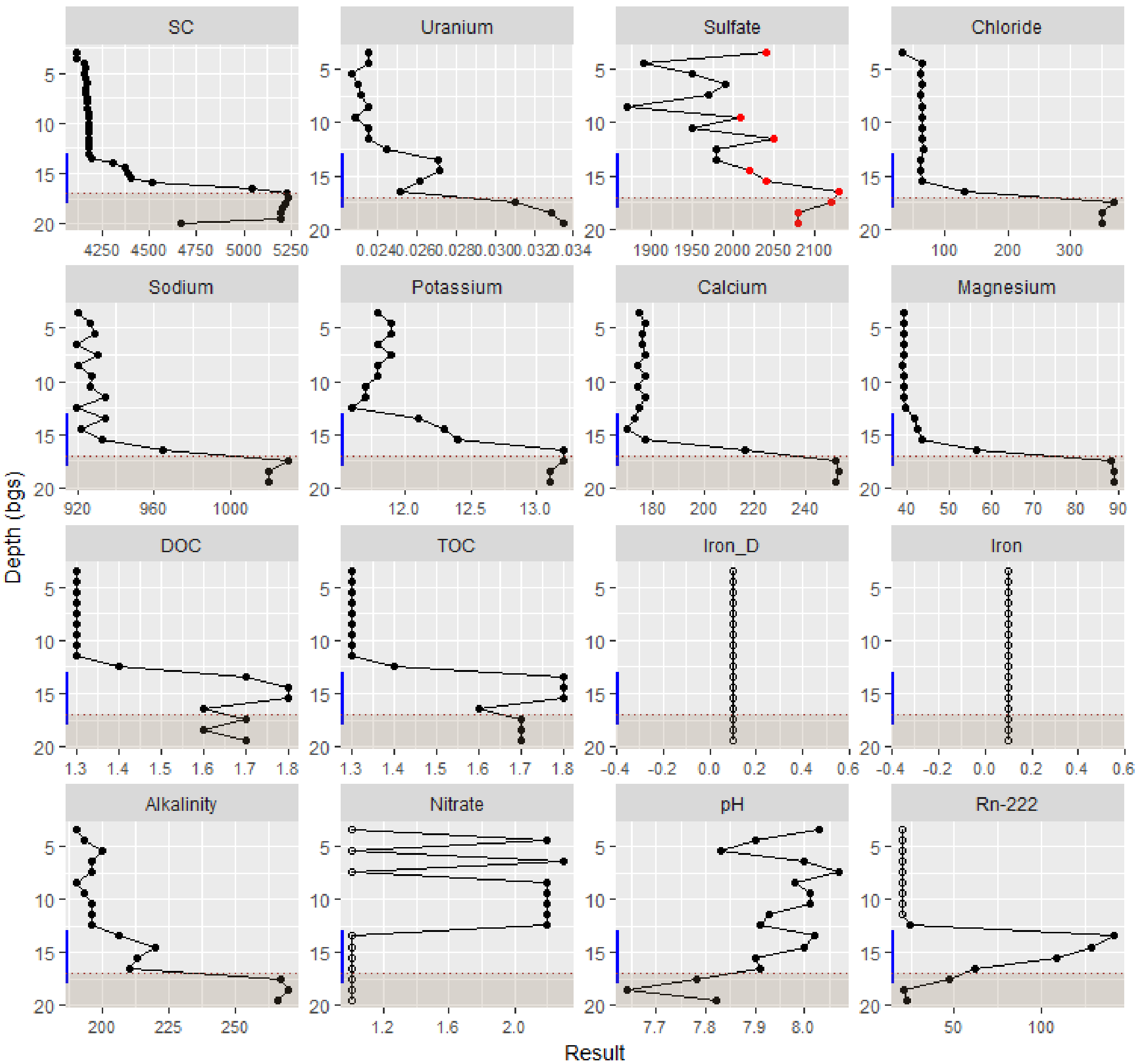
Location Map

Abbreviations:

bgs	below ground surface
DOC	dissolved and total organic carbon
Iron_D	dissolved iron (followed by total iron)
SC	specific conductance
TOC	total organic carbon

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 0620



Notes:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

| screened interval

···· bedrock contact ▭ Mancos Shale

○ below detection limit

● result exceeds corresponding 40 CFR 192 MCL or site standard

- 0.044 mg/L uranium
- 2000 mg/L sulfate
- 44 mg/L nitrate as NO_3

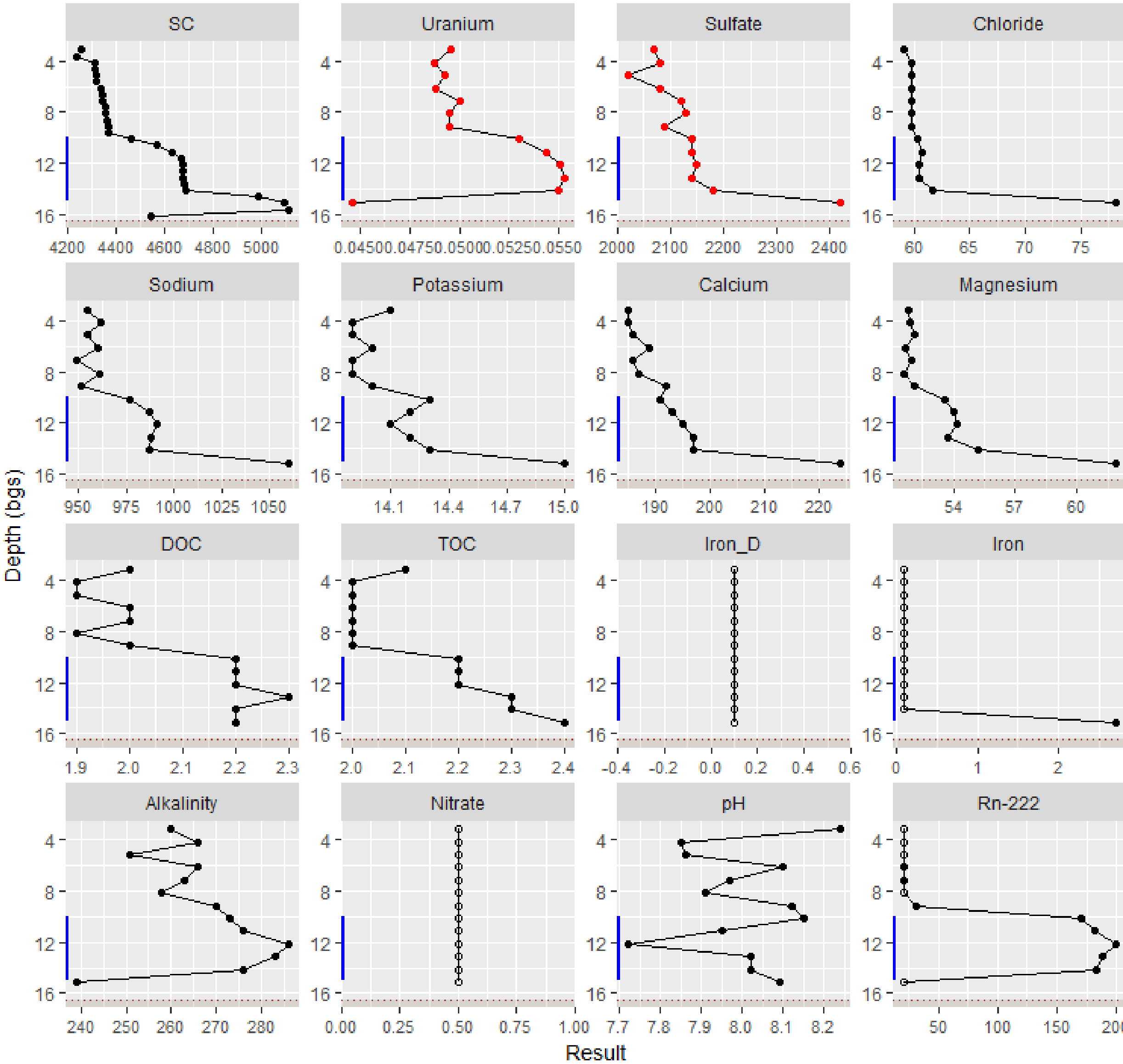
Well location shown in inset to right (adapted from Figure 39 of main text)

Location Map

Abbreviations:

bgs	below ground surface
DOC	dissolved and total organic carbon
Iron_D	dissolved iron (followed by total iron)
SC	specific conductance
TOC	total organic carbon

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 0621



Notes:

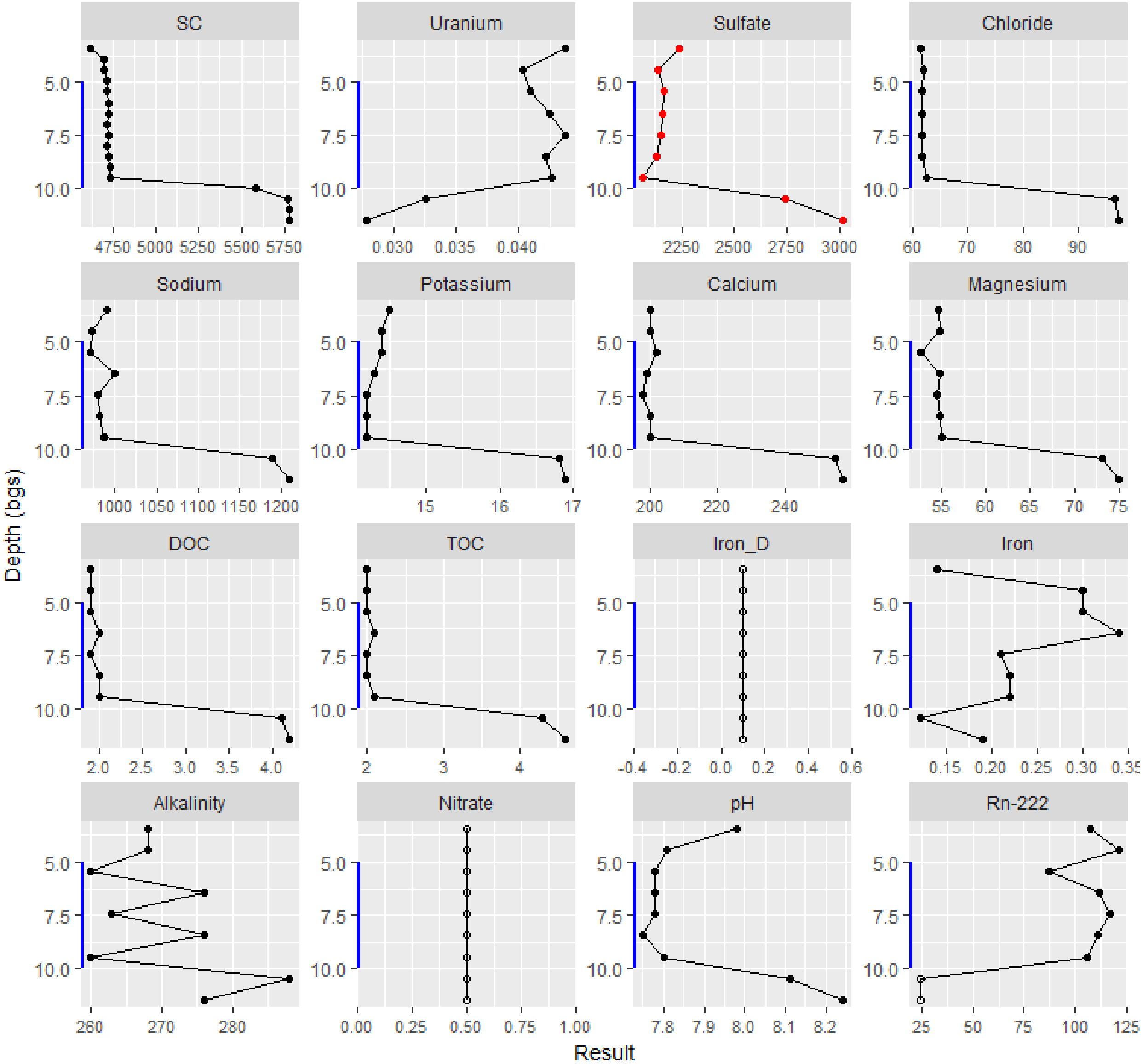
All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.
| screened interval
···· bedrock contact   Mancos Shale
○ below detection limit
● result exceeds corresponding 40 CFR 192 MCL or site standard
- 0.044 mg/L uranium
- 2000 mg/L sulfate
- 44 mg/L nitrate as NO_3

Well location shown in inset to right (adapted from Figure 39 of main text)

Location Map

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 0622



Notes:

All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.

| screened interval

···· bedrock contact ▭ Mancos Shale

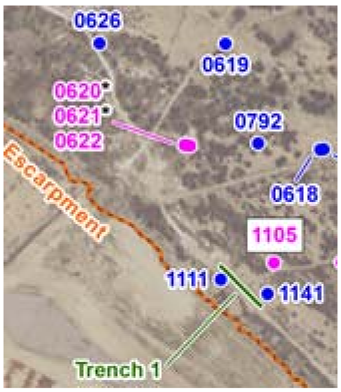
○ below detection limit

● result exceeds corresponding 40 CFR 192 MCL or site standard

- 0.044 mg/L uranium
- 2000 mg/L sulfate
- 44 mg/L nitrate as NO_3

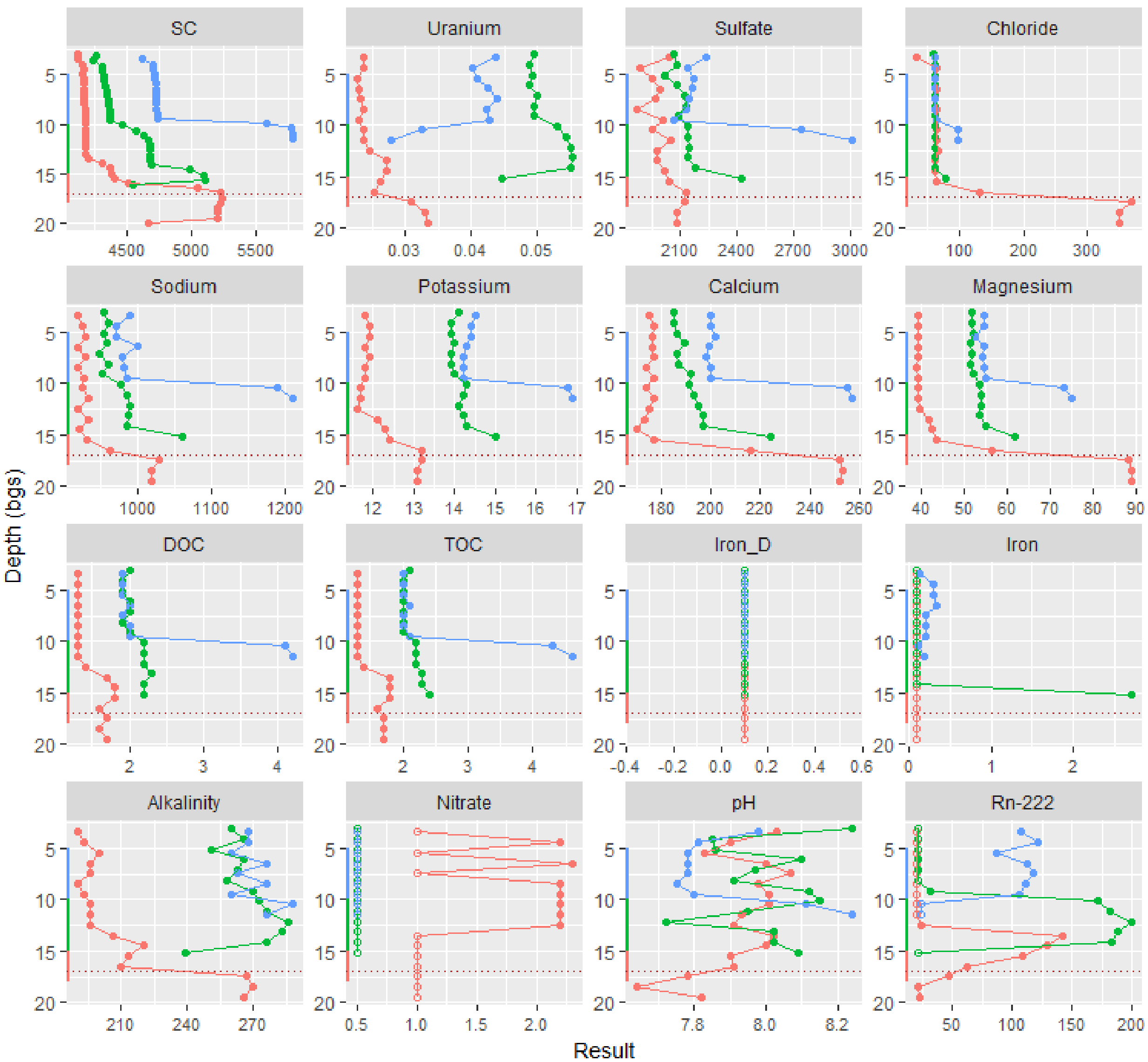
Well location shown in inset to right (adapted from Figure 39 of main text)

Location Map



Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Colocated Well Trio 0620 (orange) /0621 (green) /0622 (blue)



Notes:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

| screened interval

···· bedrock contact Mancos Shale

○ below detection limit

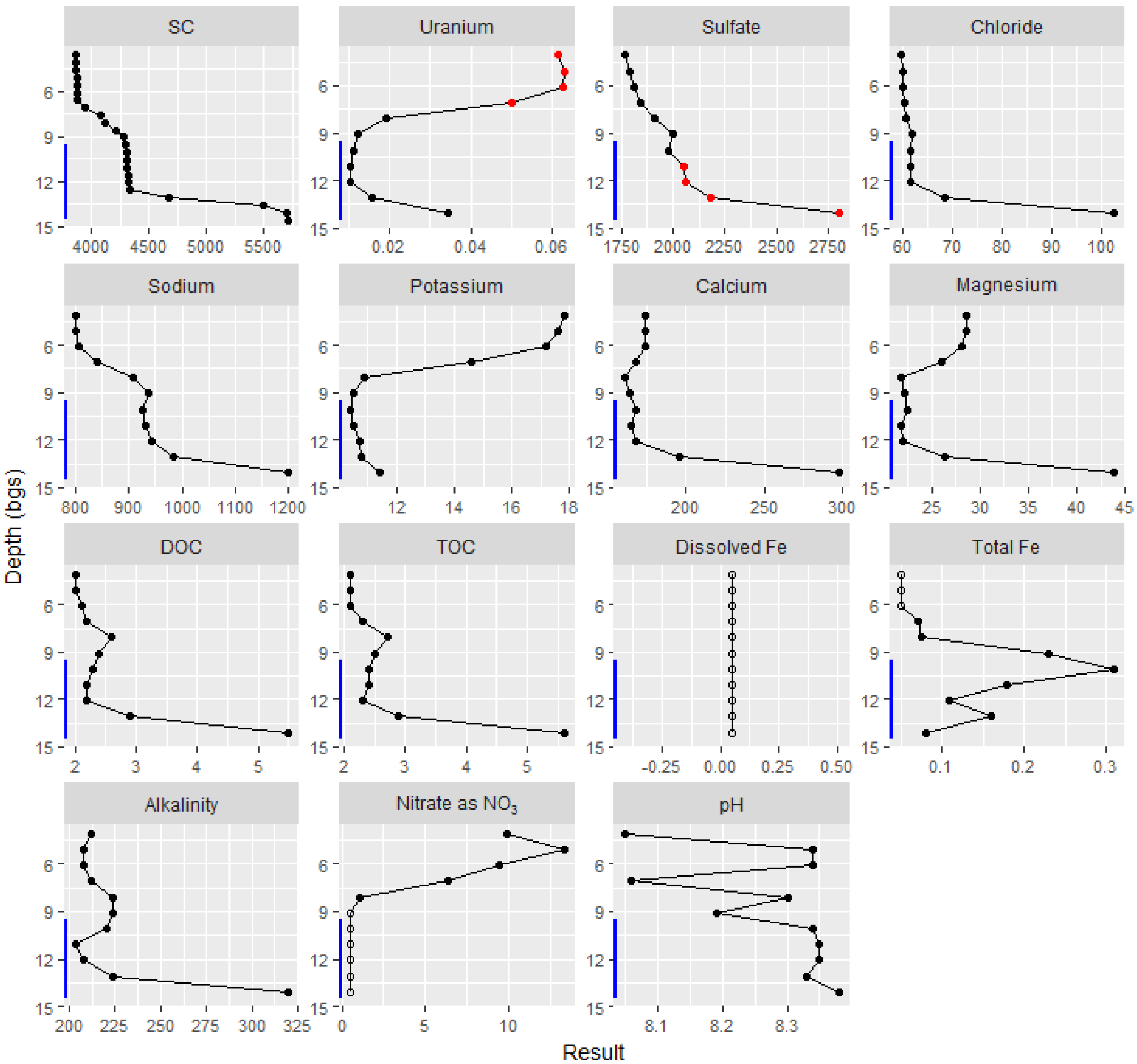
● result exceeds corresponding 40 CFR 192 MCL or site standard

- 0.044 mg/L uranium
- 2000 mg/L sulfate
- 44 mg/L nitrate as NO_3

Well location shown in inset to right (adapted from Figure 39 of main text)

Location Map

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Well 0626

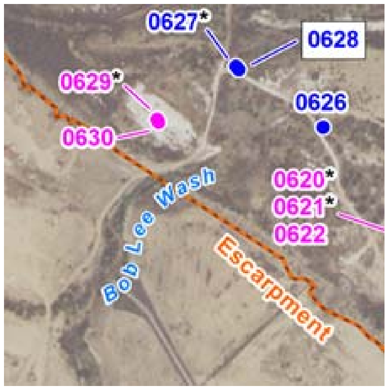


Notes:
All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.
Mancos Shale (bedrock) contact at 19 ft bgs so not shown here.
| screened interval
····· bedrock contact; Mancos Shale
● Red symbols denote results exceeding corresponding standard:
0.044 mg/L uranium; 2000 mg/L sulfate; and 44 mg/L nitrate as NO_3
○ Hollow symbol denotes result below detection limit.

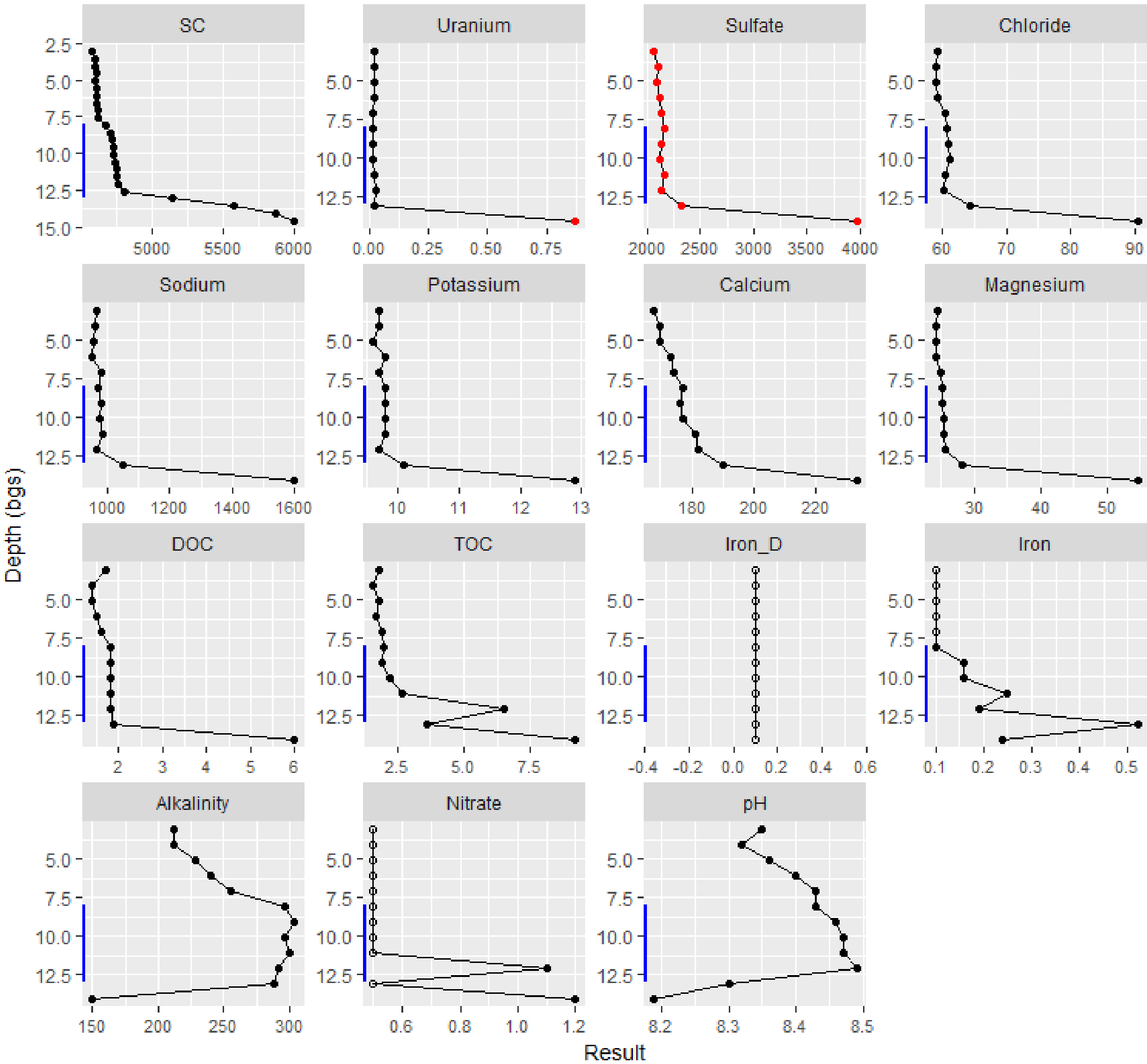
Well 0626 is located west of Trench 1 near the base of the escarpment, as shown in the inset to right (adapted from Figure 39 of main text)

Abbreviations
bgs below ground surface
DOC dissolved organic carbon
Fe iron
SC specific conductance
TOC total organic carbon

Location Map

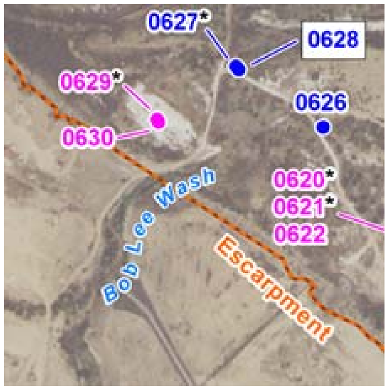


Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Well 0627

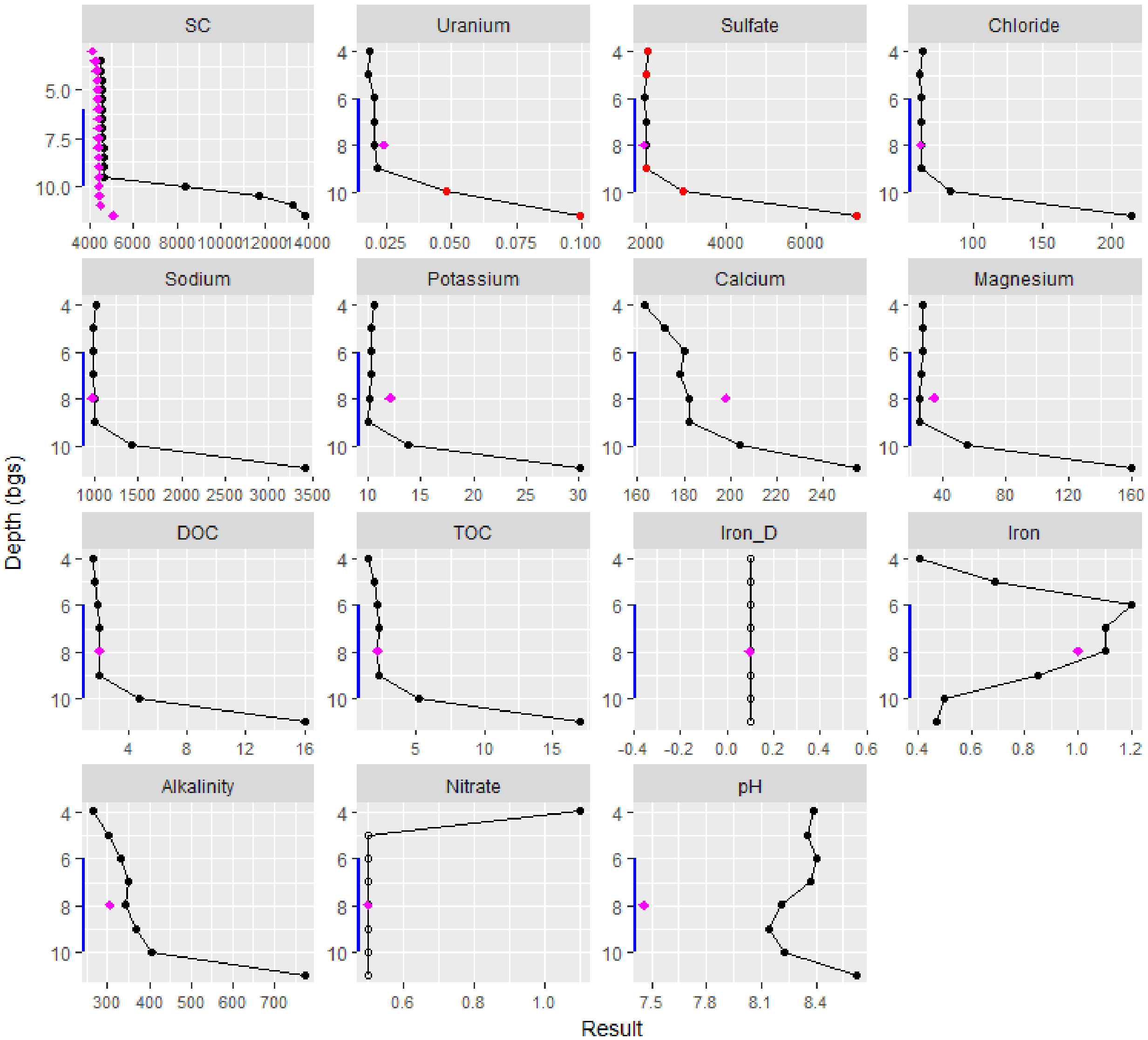


Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.
Mancos Shale (bedrock) contact at 19 ft bgs so not shown here.
| screened interval
····· bedrock contact; Mancos Shale
● Red symbols denote results exceeding corresponding standard:
0.044 mg/L uranium; 2000 mg/L sulfate; and 44 mg/L nitrate as NO_3
○ Hollow symbol denotes result below detection limit.

Location Map

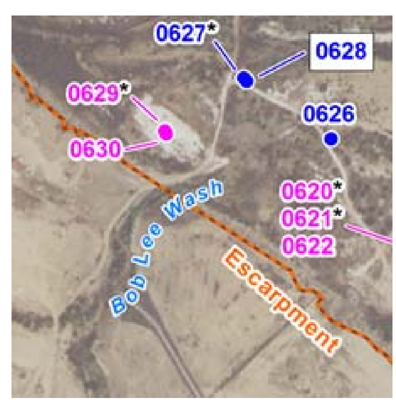


Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Well 0628



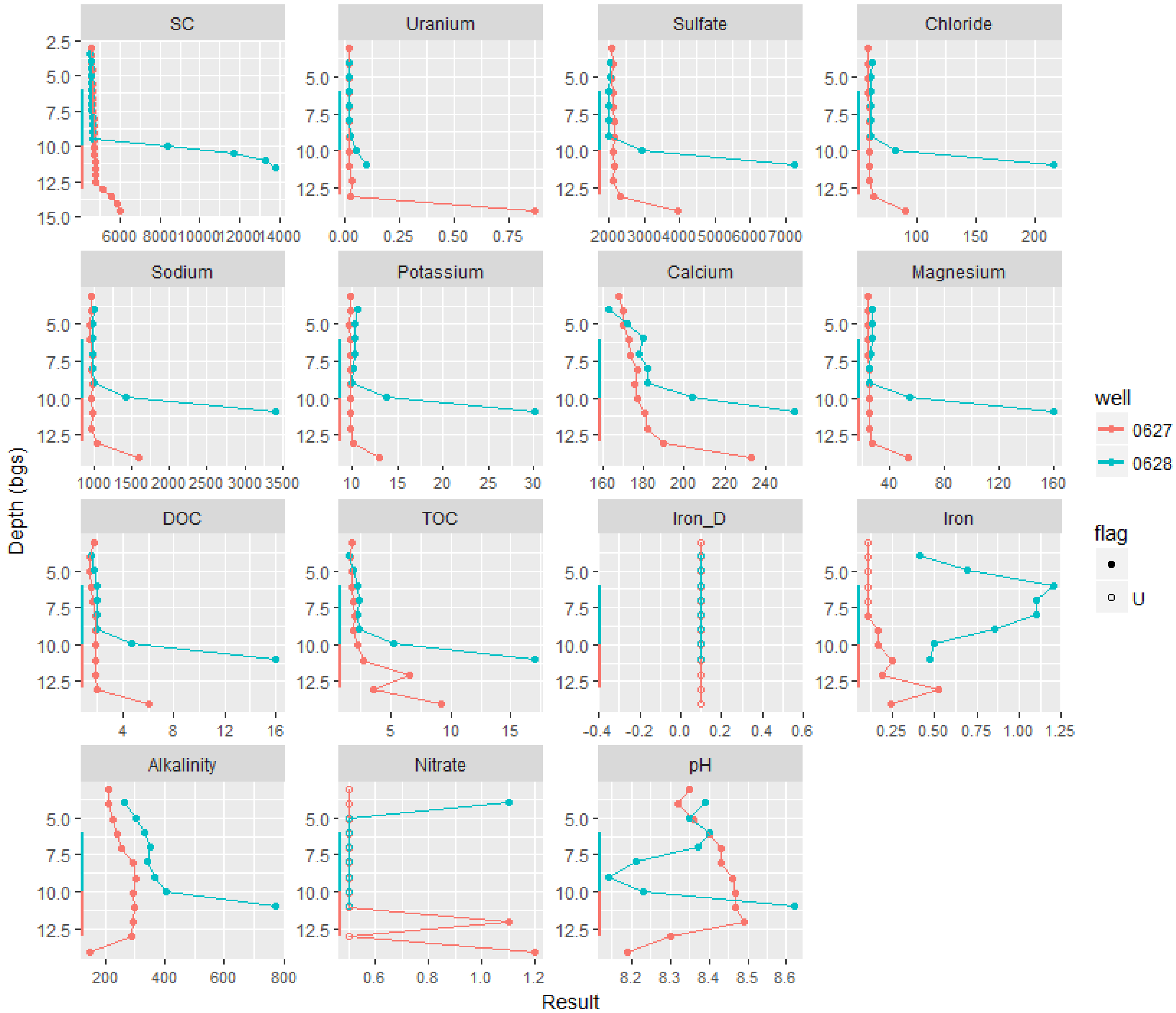
Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.
Mancos Shale (bedrock) contact at 19 ft bgs so not shown here.
| screened interval
····· bedrock contact; Mancos Shale
● Red symbols denote results exceeding corresponding standard:
0.044 mg/L uranium; 2000 mg/L sulfate; and 44 mg/L nitrate as NO_3
○ Hollow symbol denotes result below detection limit.

Location Map



Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Well 0627/0628 Colocated Well Pair



Notes:

All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.

Mancos Shale (bedrock) contact at 19 ft bgs so not shown here.

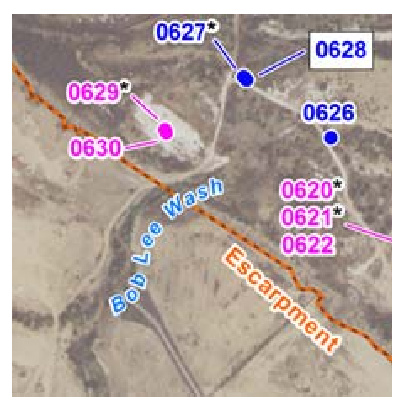
| screened interval

····· bedrock contact; Mancos Shale

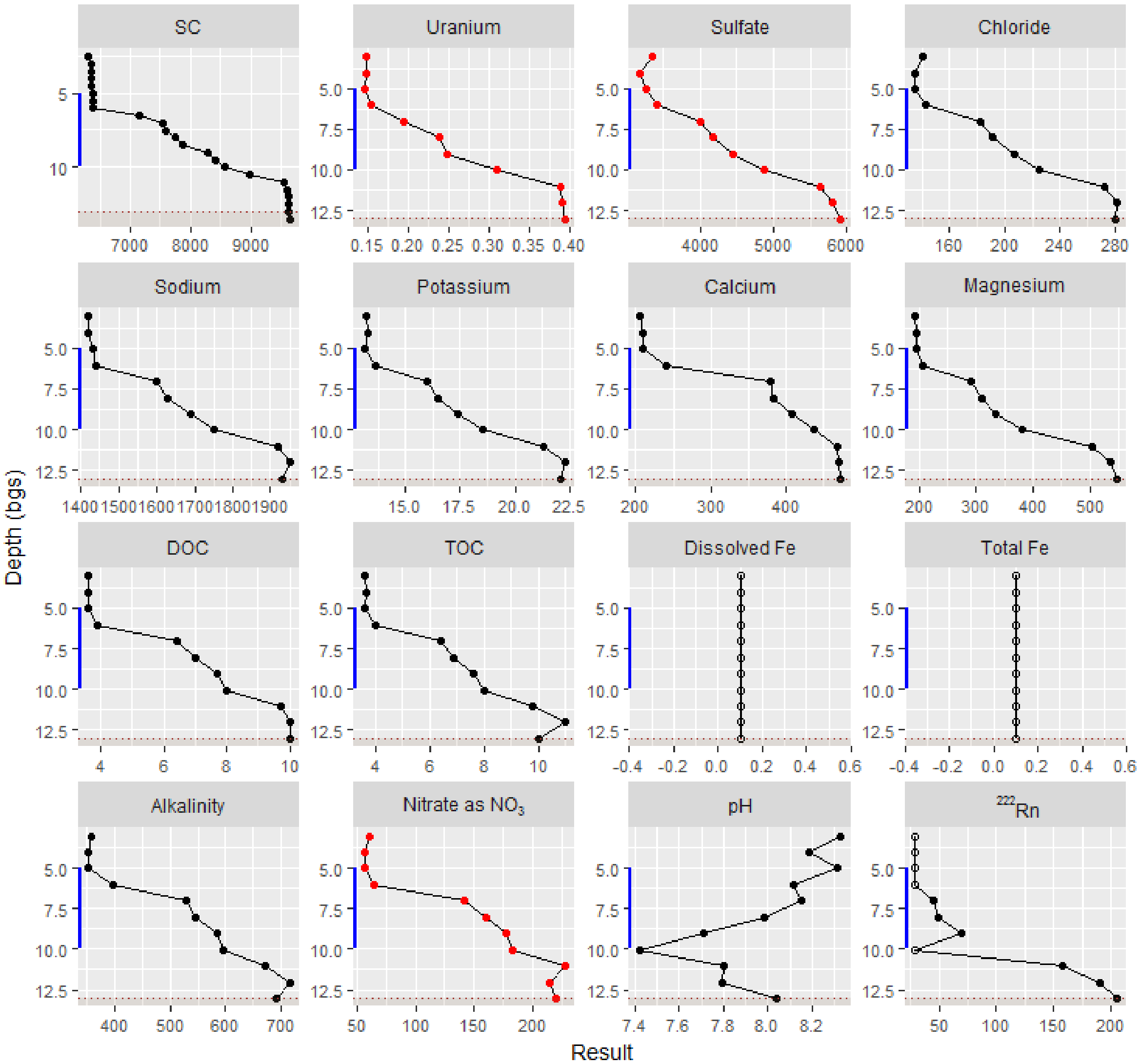
● Red symbols denote results exceeding corresponding standard: 0.044 mg/L uranium; 2000 mg/L sulfate; and 44 mg/L nitrate as NO_3

○ Hollow symbol denotes result below detection limit.

Location Map



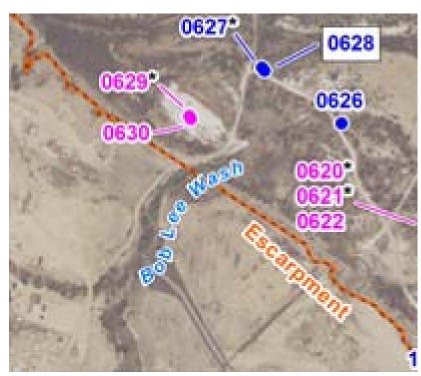
Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 0630



bgs below ground surface
DOC, TOC dissolved and total organic carbon
Fe iron
SC specific conductance
| screened interval
···· bedrock contact Mancos Shale
○ below detection limit
● result exceeds corresponding 40 CFR 192 or site standard

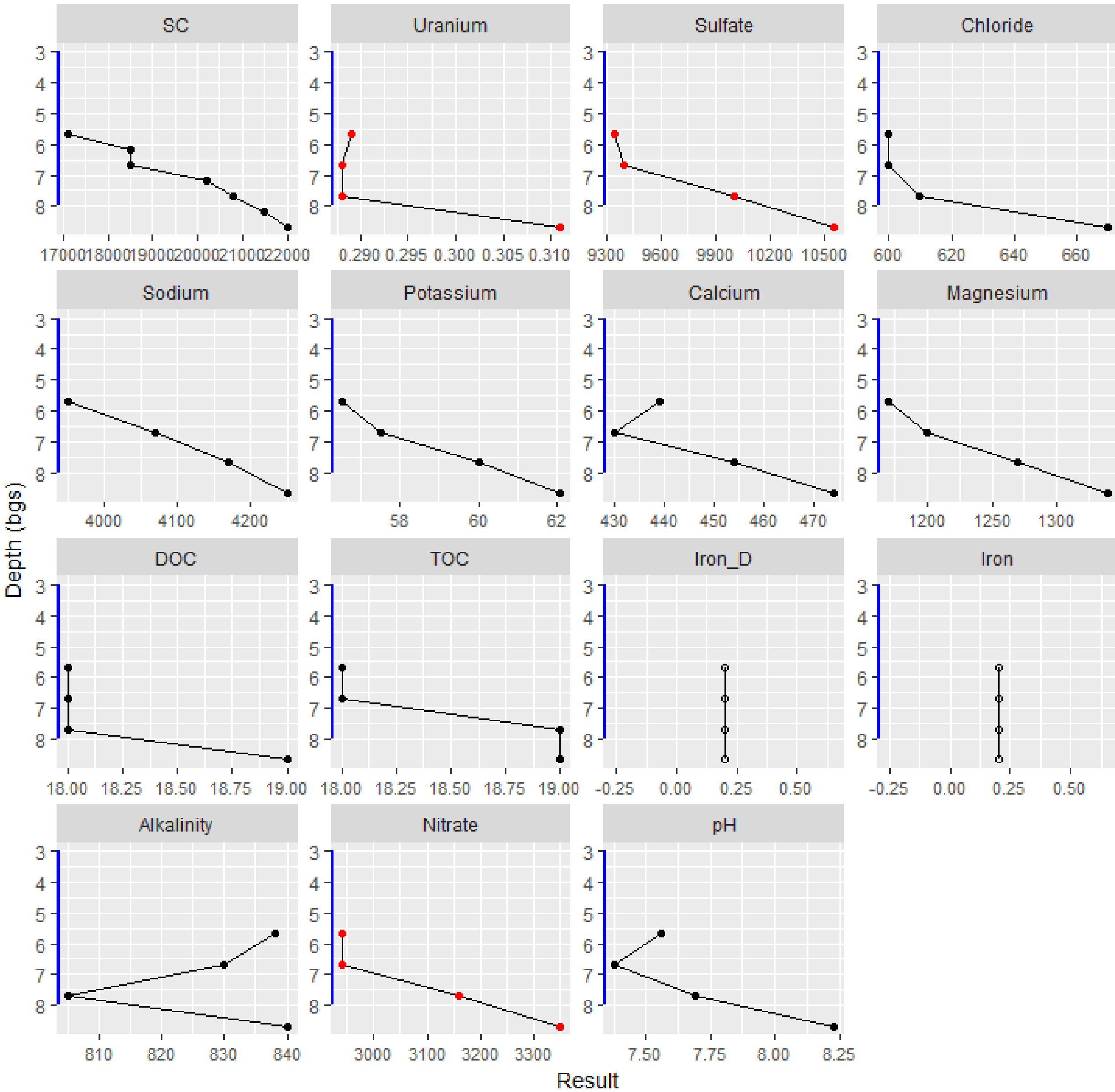
- 0.044 mg/L uranium
- 2000 mg/L sulfate
- 44 mg/L nitrate as NO_3

Location Map



Notes:
Well location shown in inset to right (adapted from Figure 39 of main text)
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L);
alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 0735



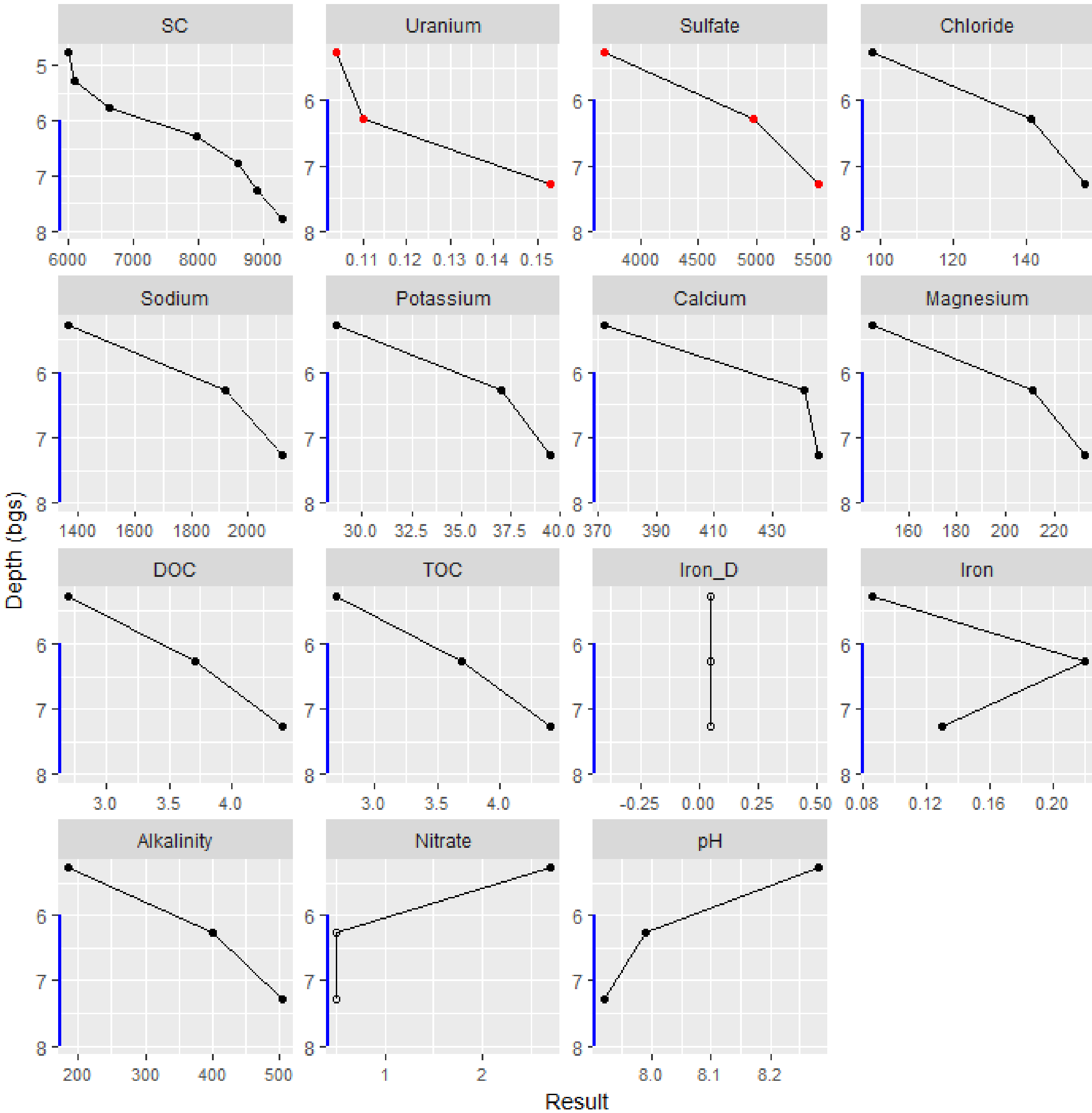
| Screened interval
···· Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 0792



| Screened interval

···· Bedrock contact

Mancos Shale

○ BDL result

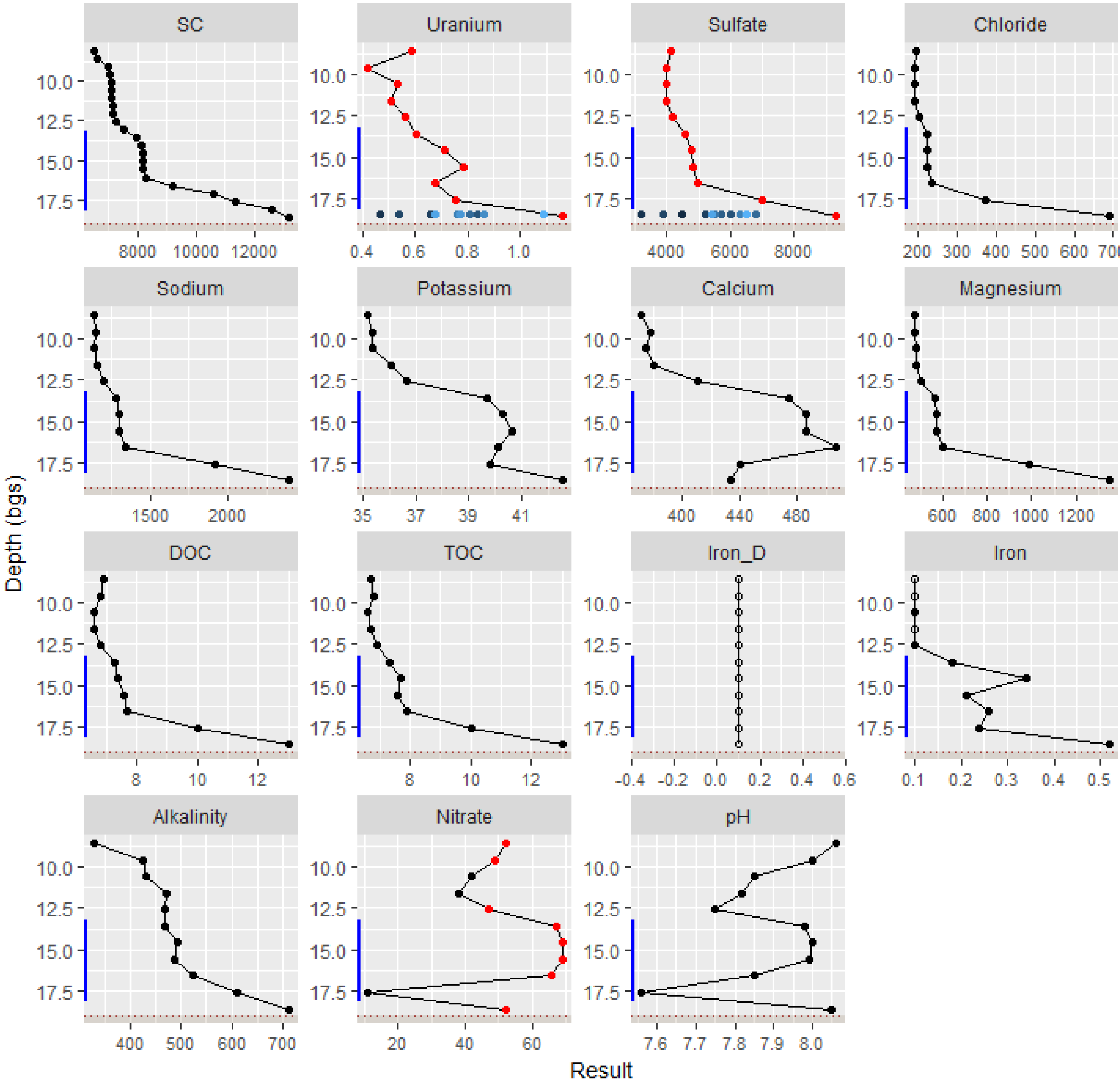
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 0857

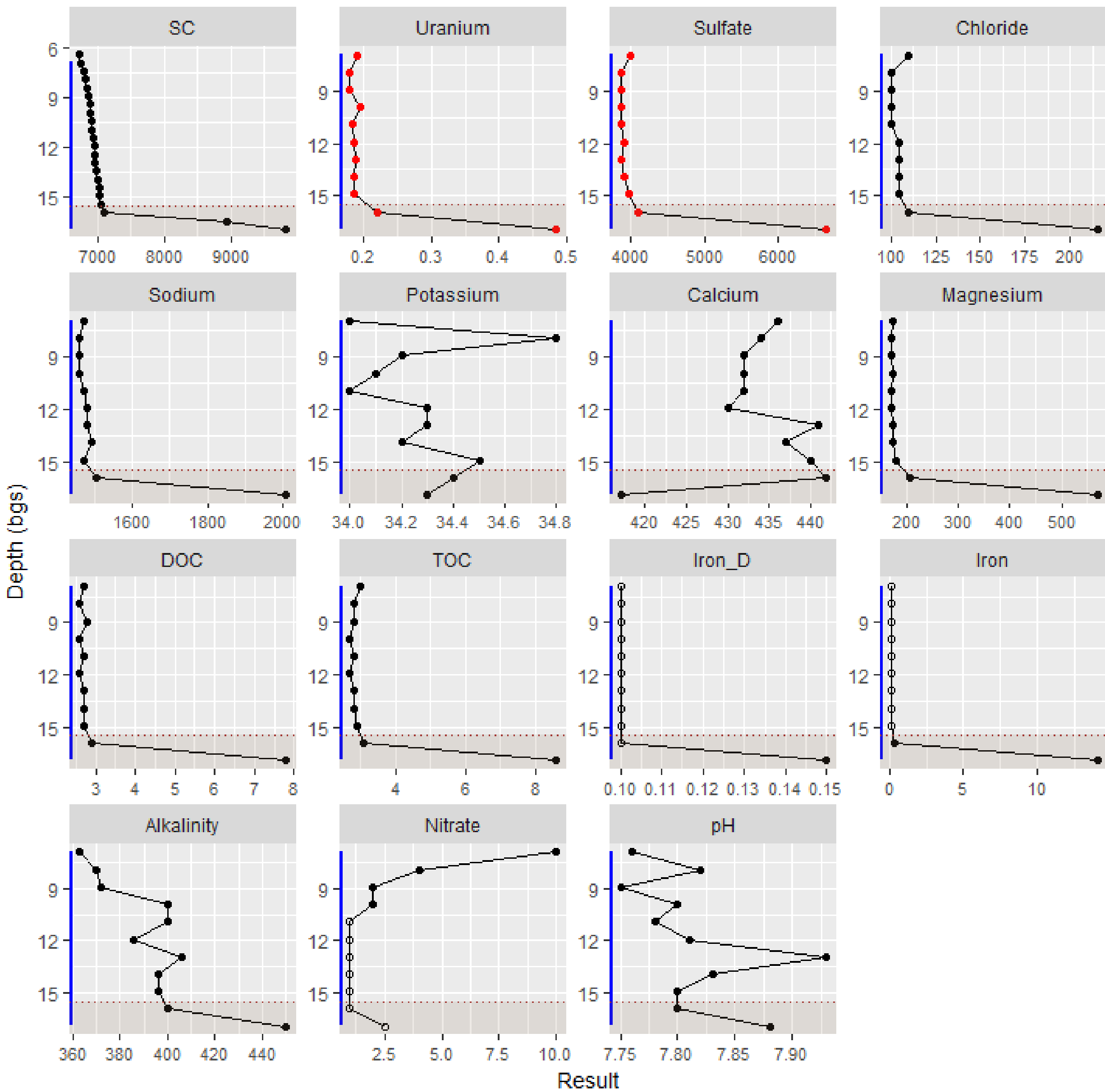


| Screened interval
.... Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Notes:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.
Blue dots shown above for uranium and sulfate reflect historical range based on routine monitoring results. Color reflects date, where more recent measurements are lighter, and older results are darker.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1008



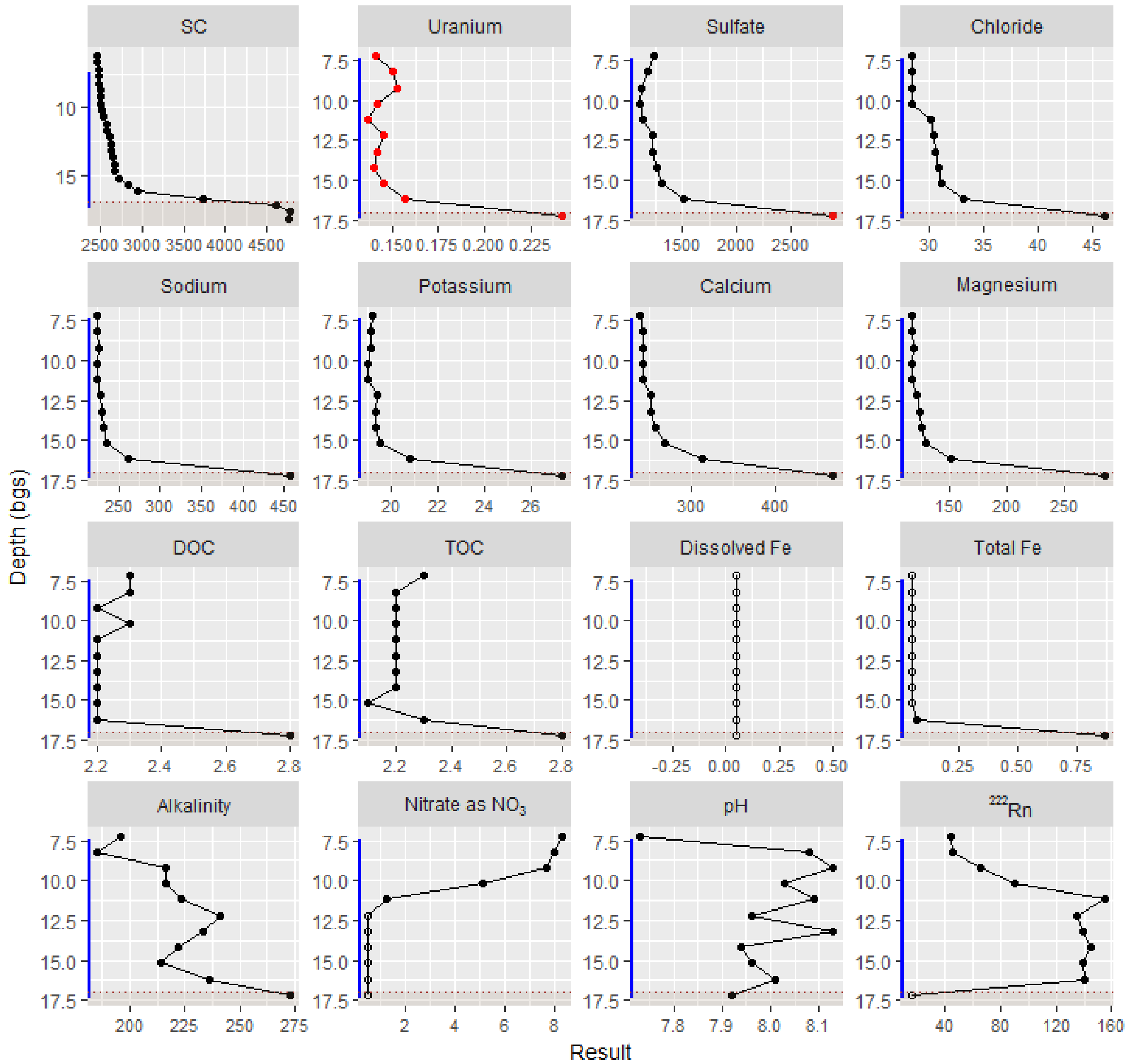
| Screened interval
⋯ Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 1009



| Screened interval

···· Bedrock contact

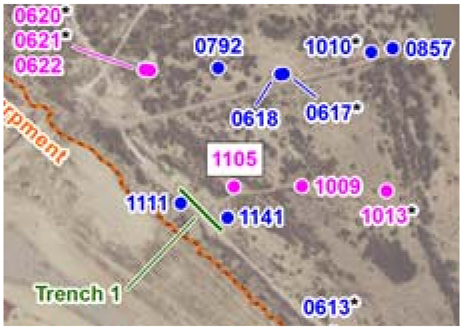
Mancos Shale

○ BDL result

● Result exceeds corresponding 40 CFR 192 MCL or background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Location Map

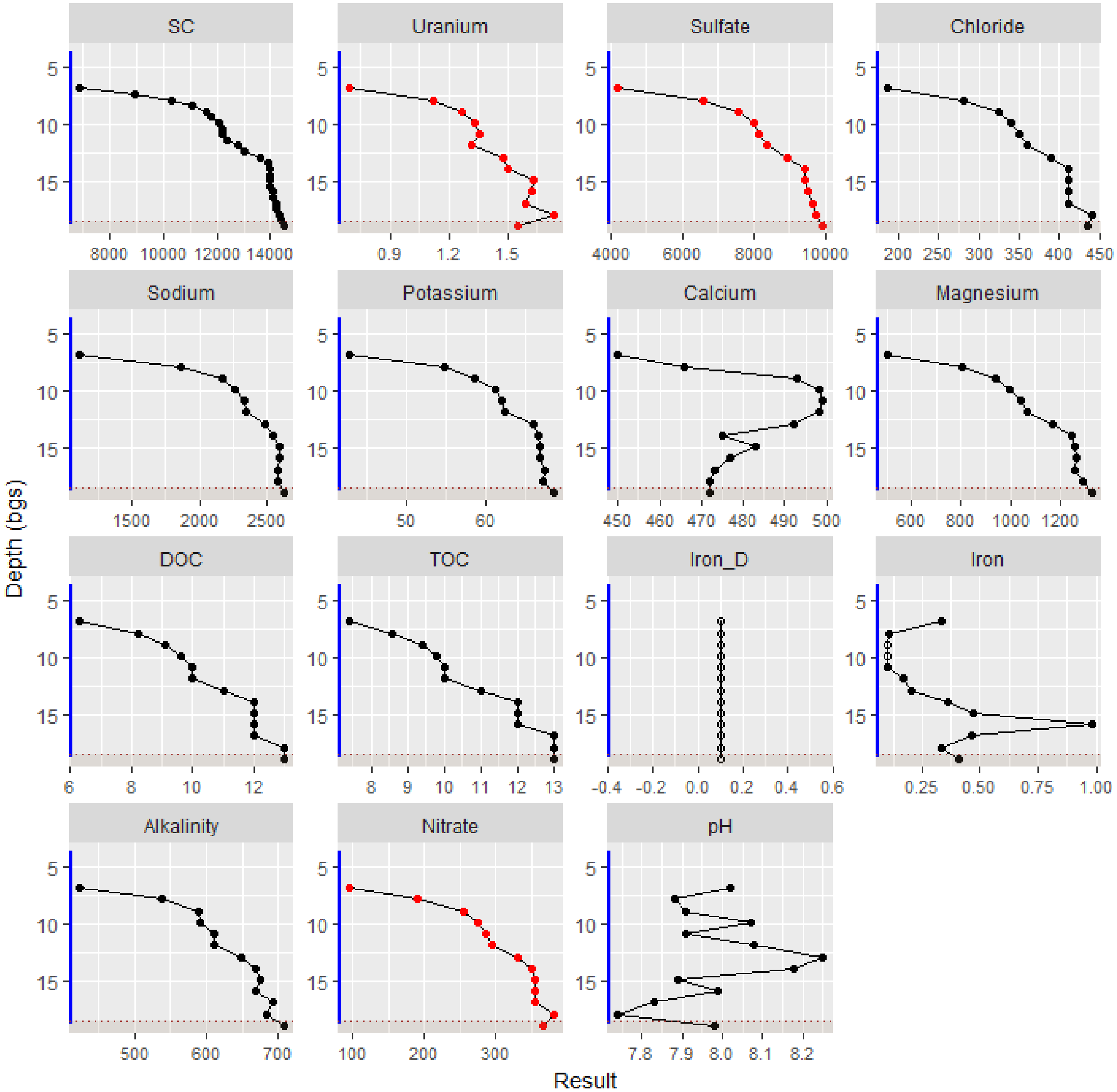


Notes:

Well location shown in inset to right (adapted from Figure 39 of main text)

All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1010

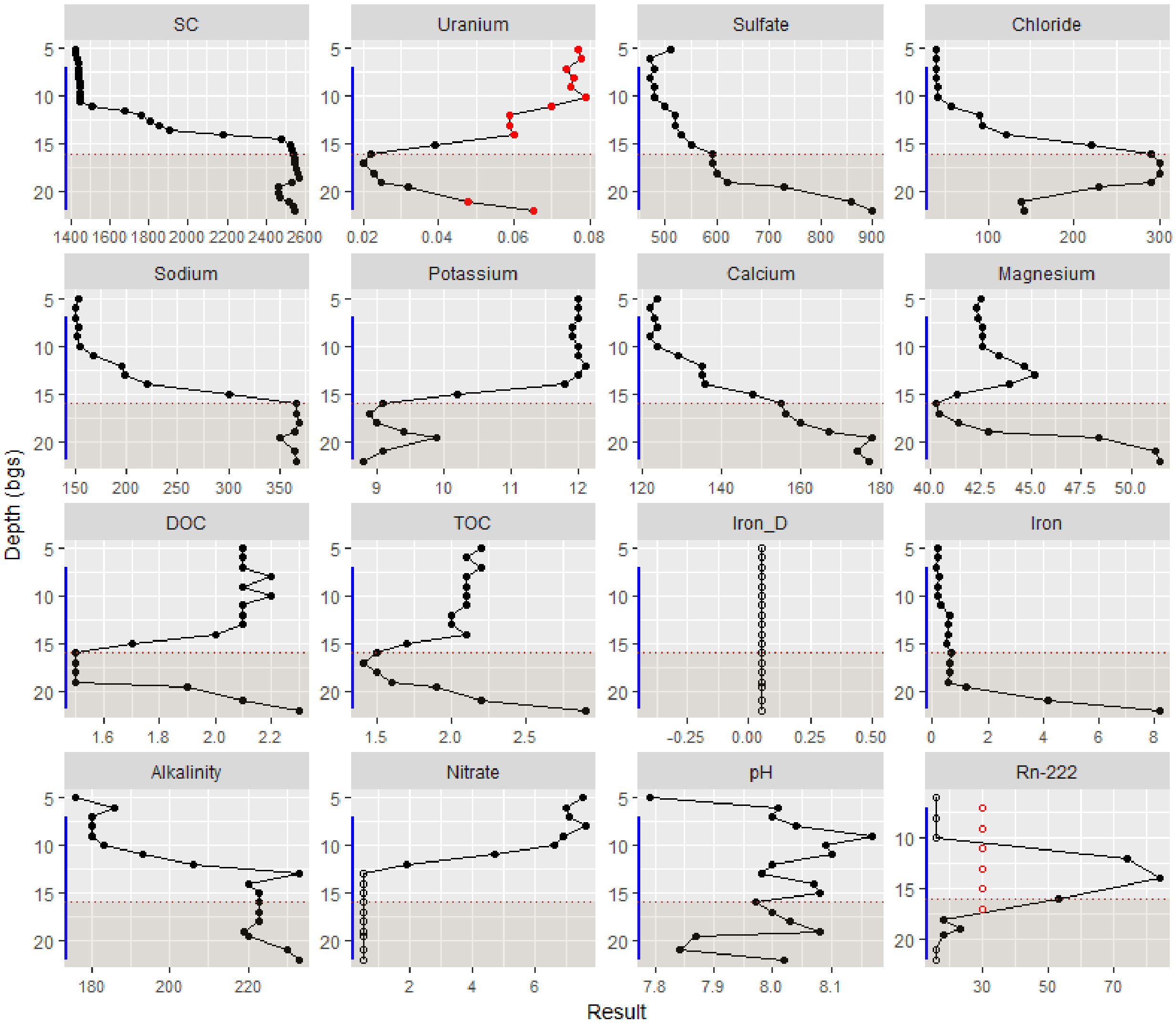


| Screened interval
···· Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1013

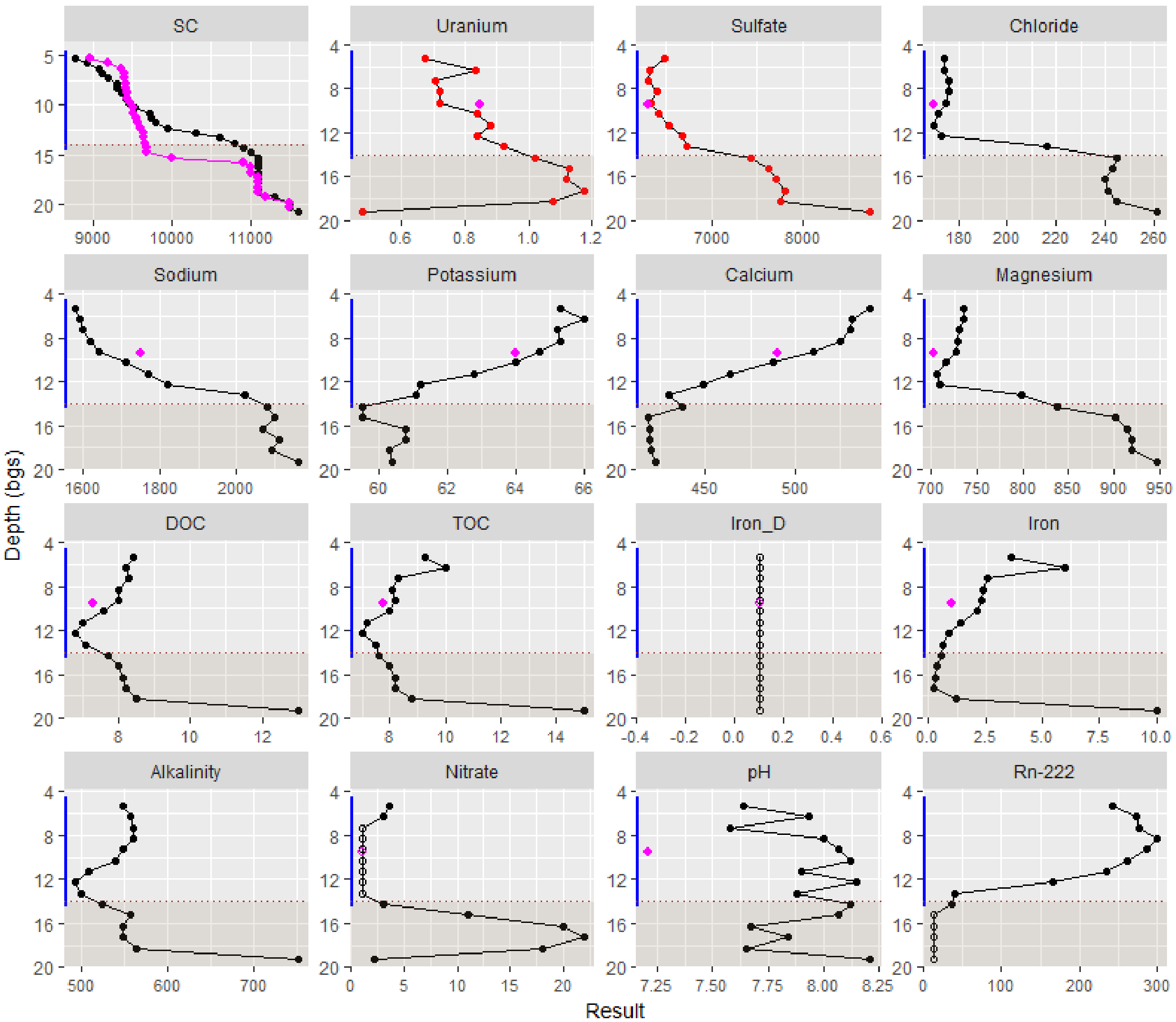


| Screened interval
···· Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1105

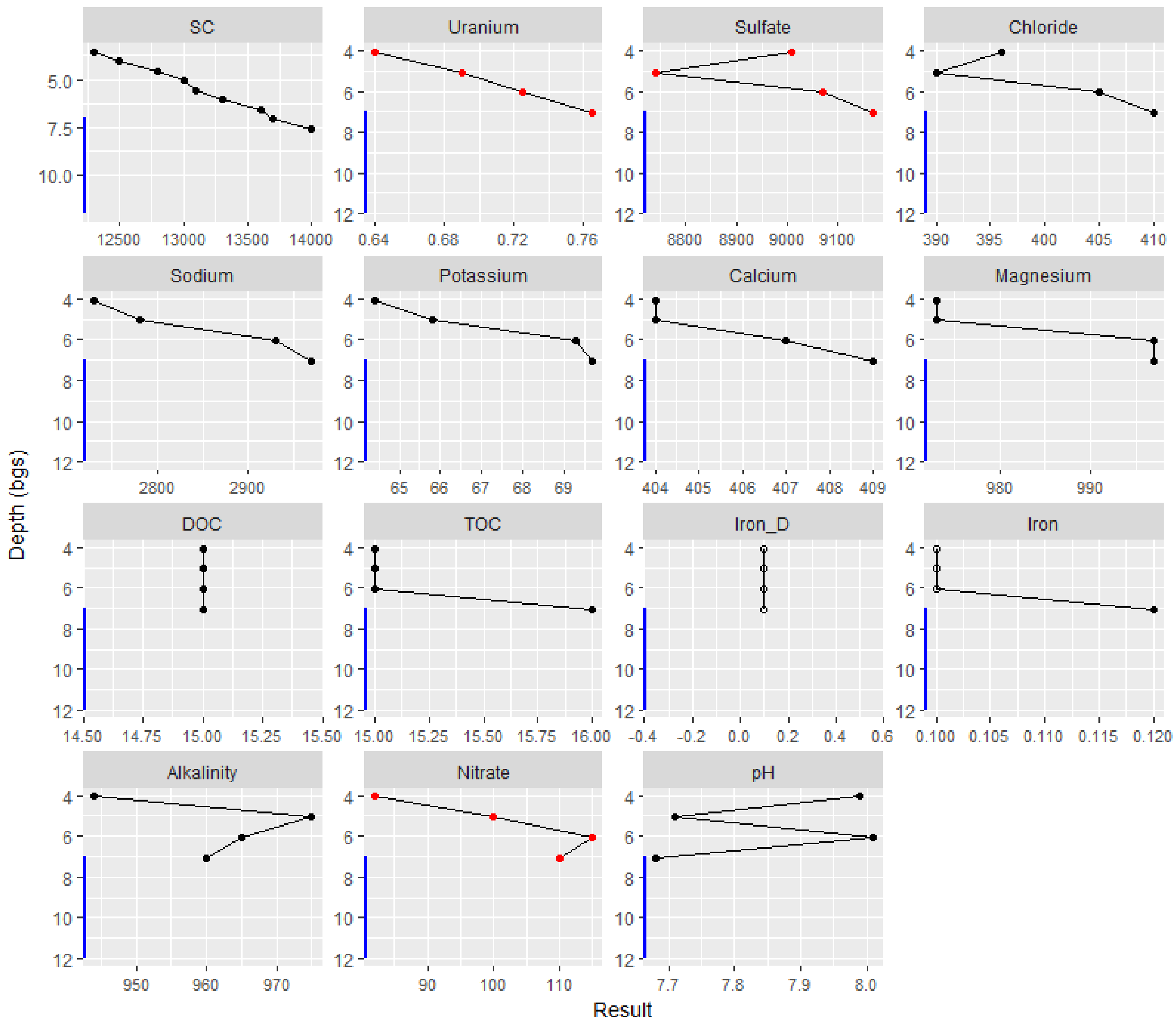


| Screened interval
⋯ Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (μS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1111

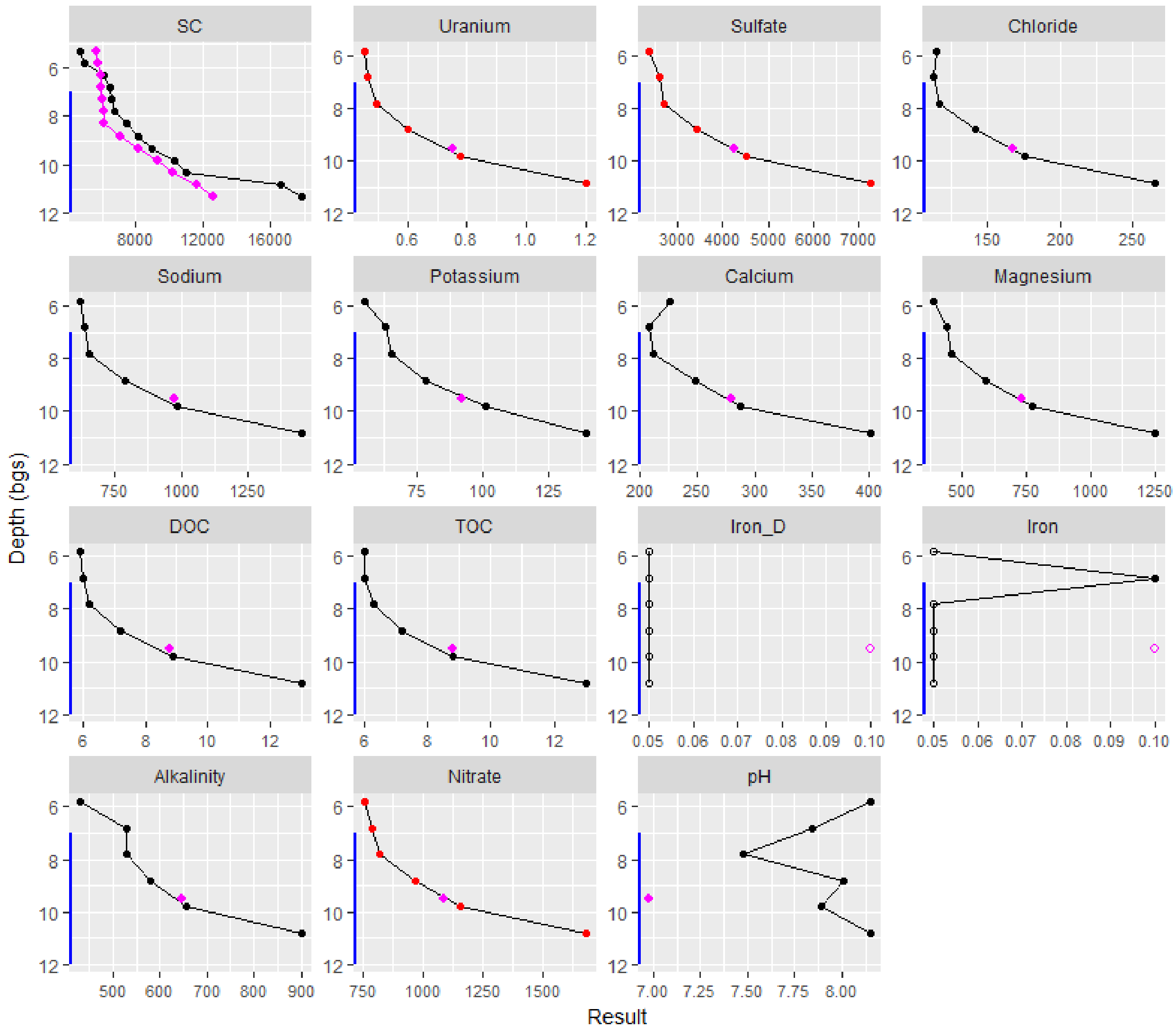


| Screened interval
···· Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1115

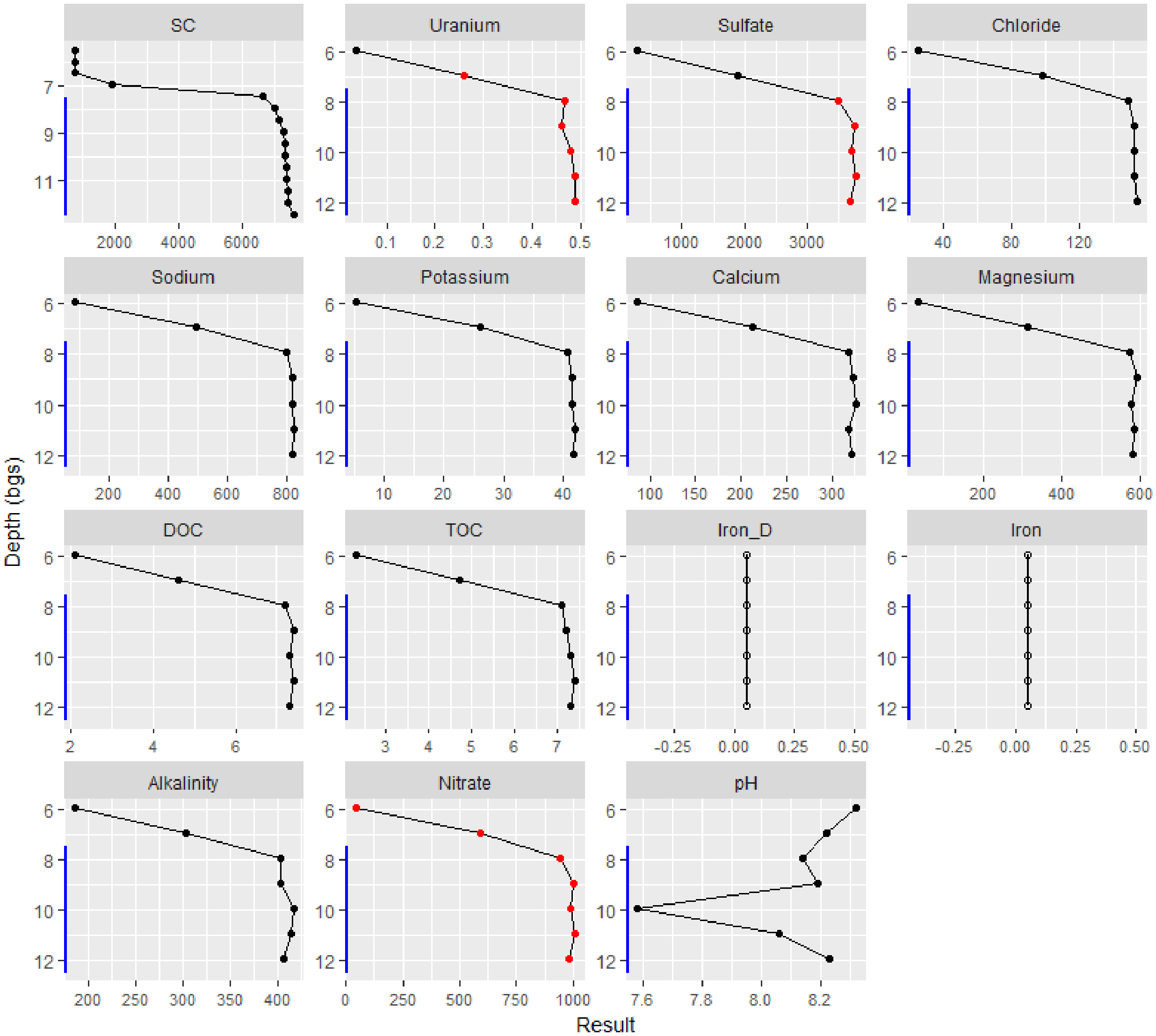


| Screened interval
···· Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1126



| Screened interval

···· Bedrock contact

Mancos Shale

○ BDL result

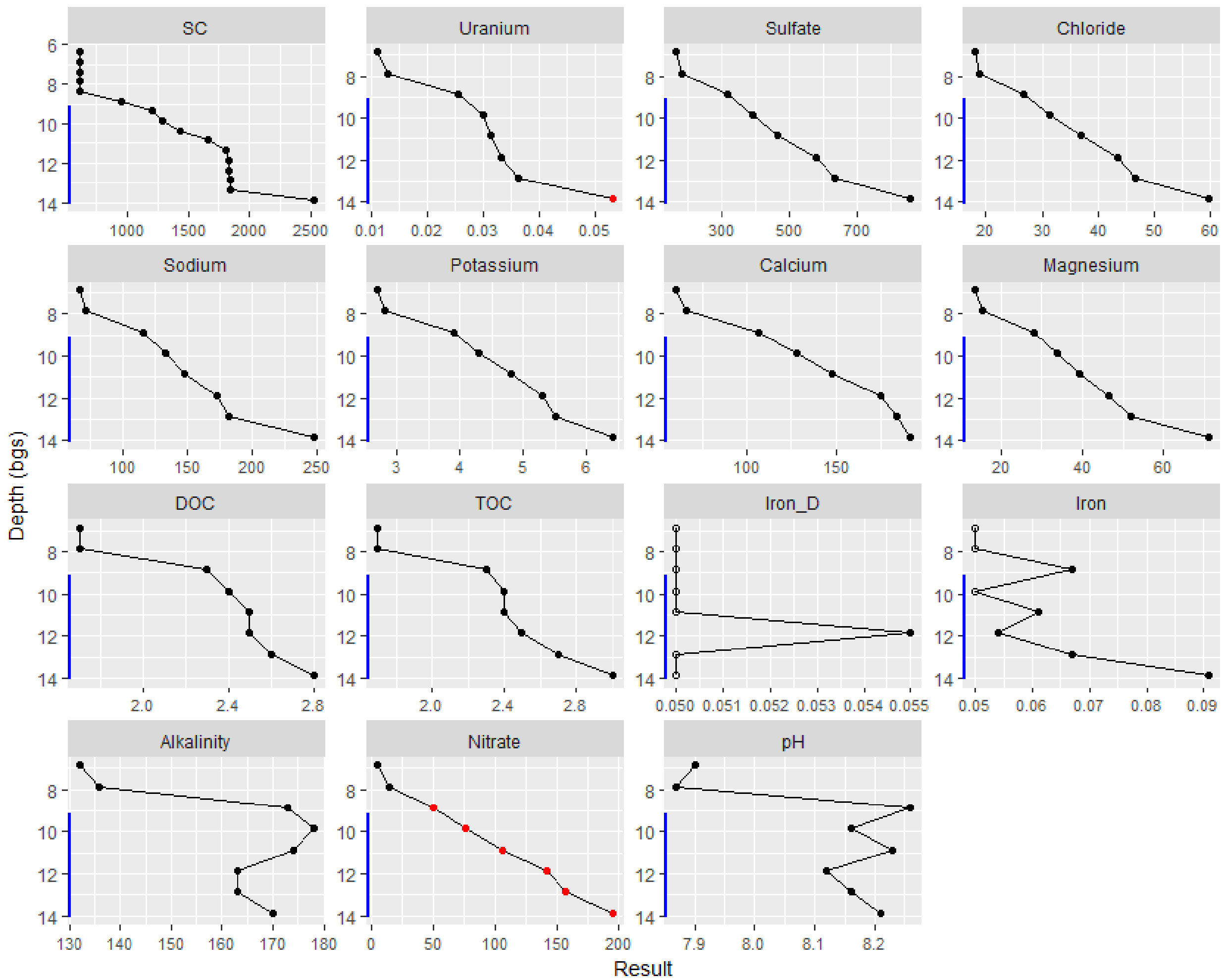
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 1127



| Screened interval

.... Bedrock contact

Mancos Shale

○ BDL result

● Result exceeds corresponding 40 CFR 192 MCL or site background level

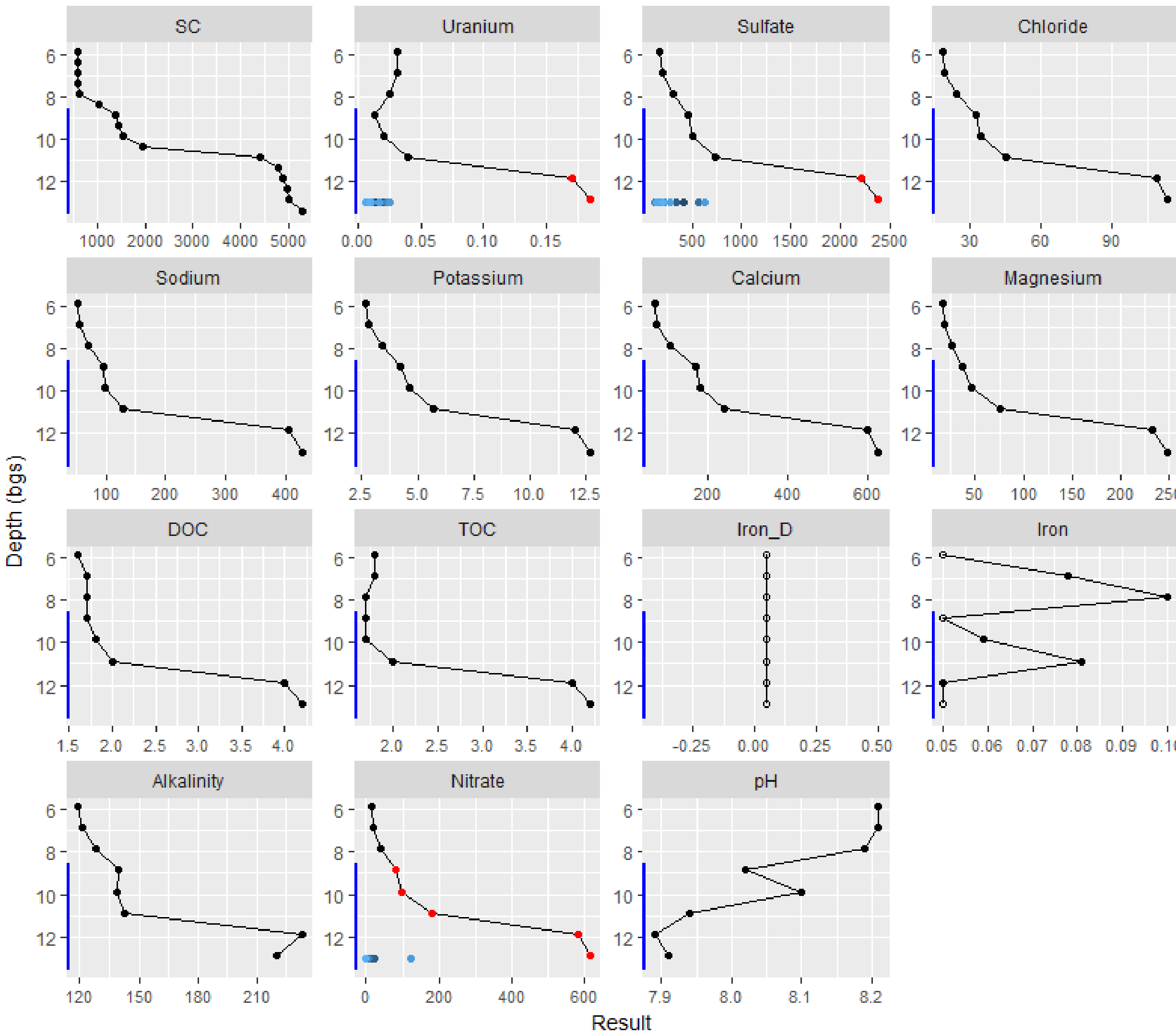
- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:

All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 1134



| Screened interval

···· Bedrock contact

Mancos Shale

○ BDL result

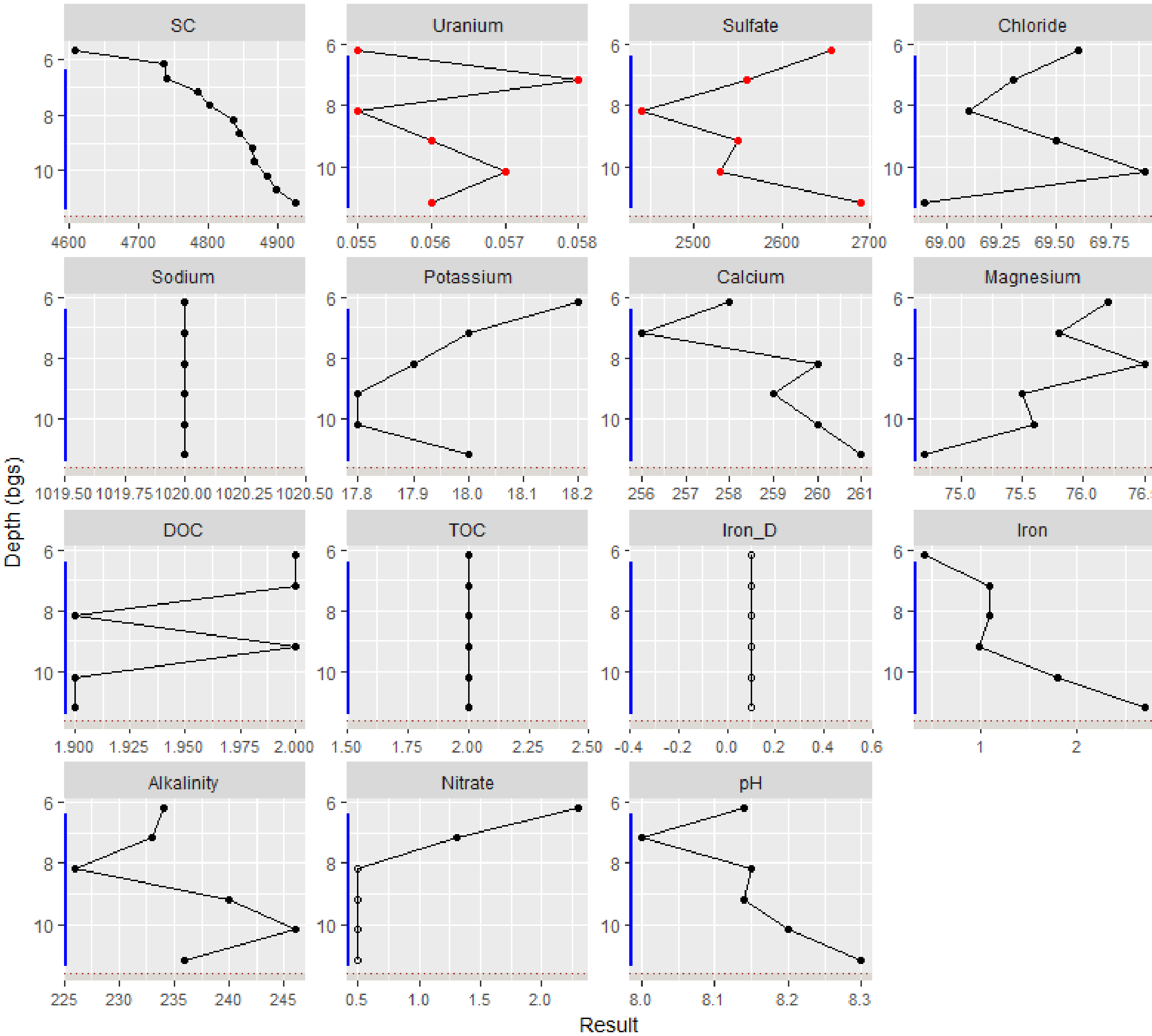
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:

All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1135

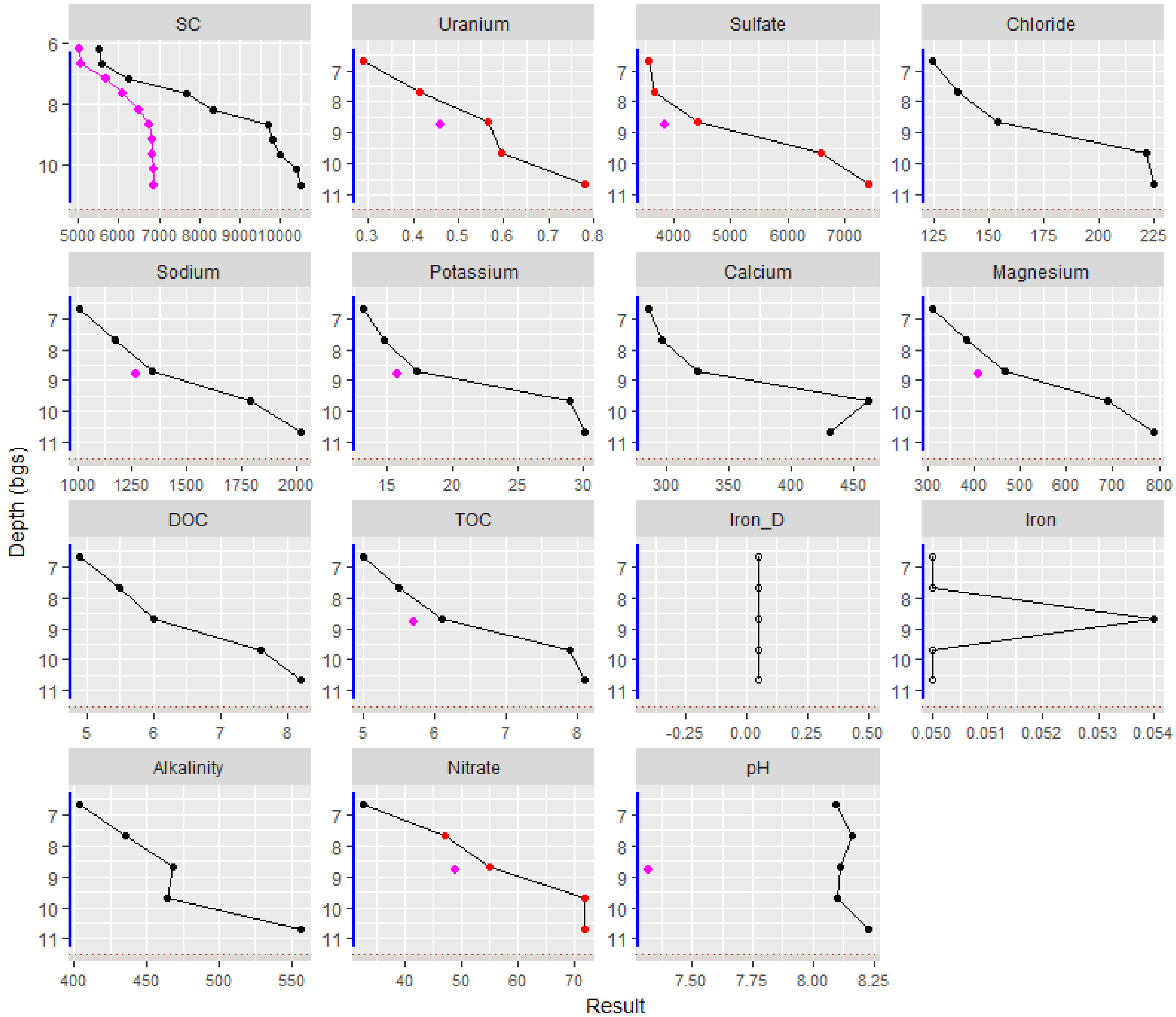


| Screened interval
···· Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1136

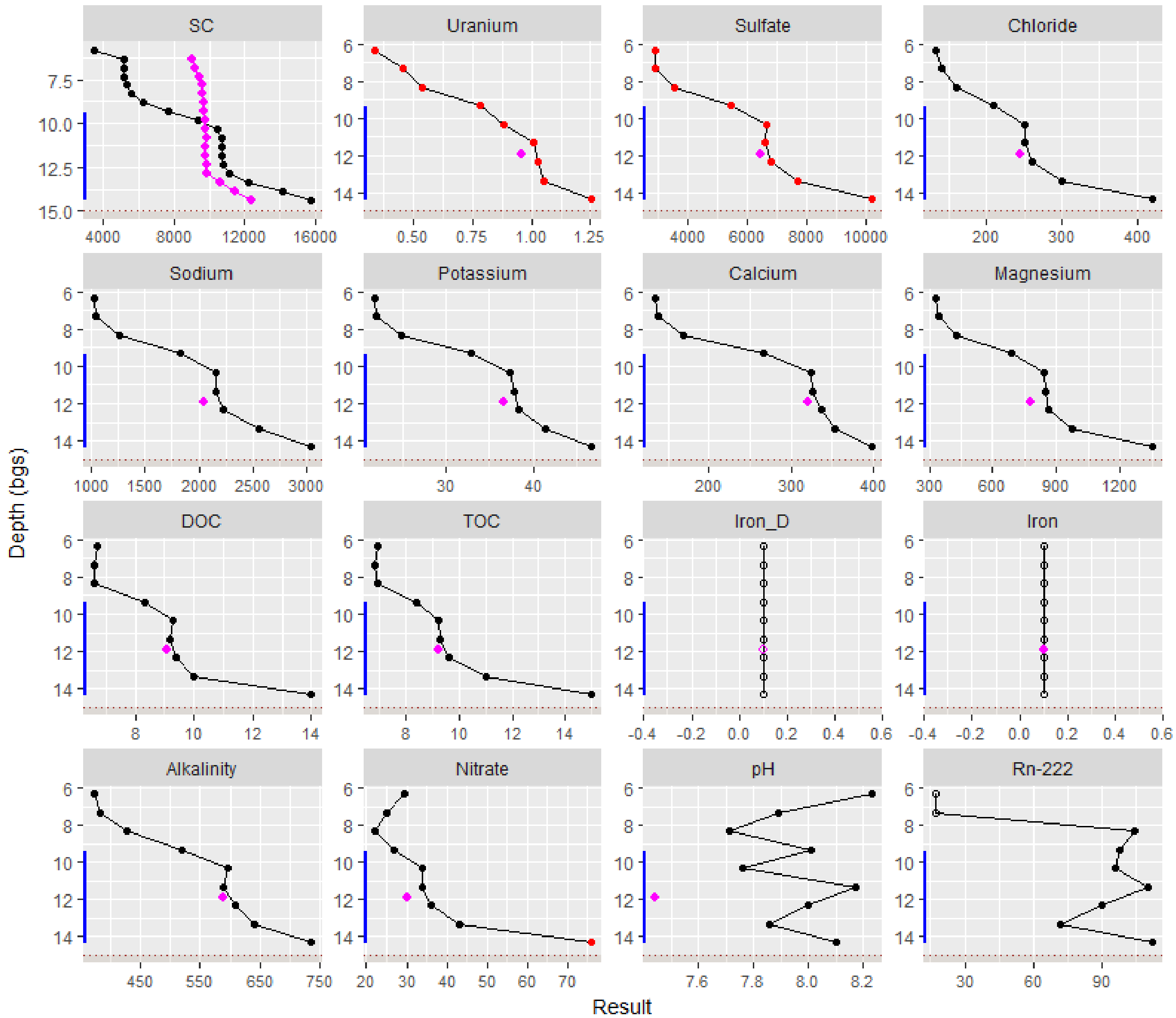


| Screened interval
⋯ Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1137

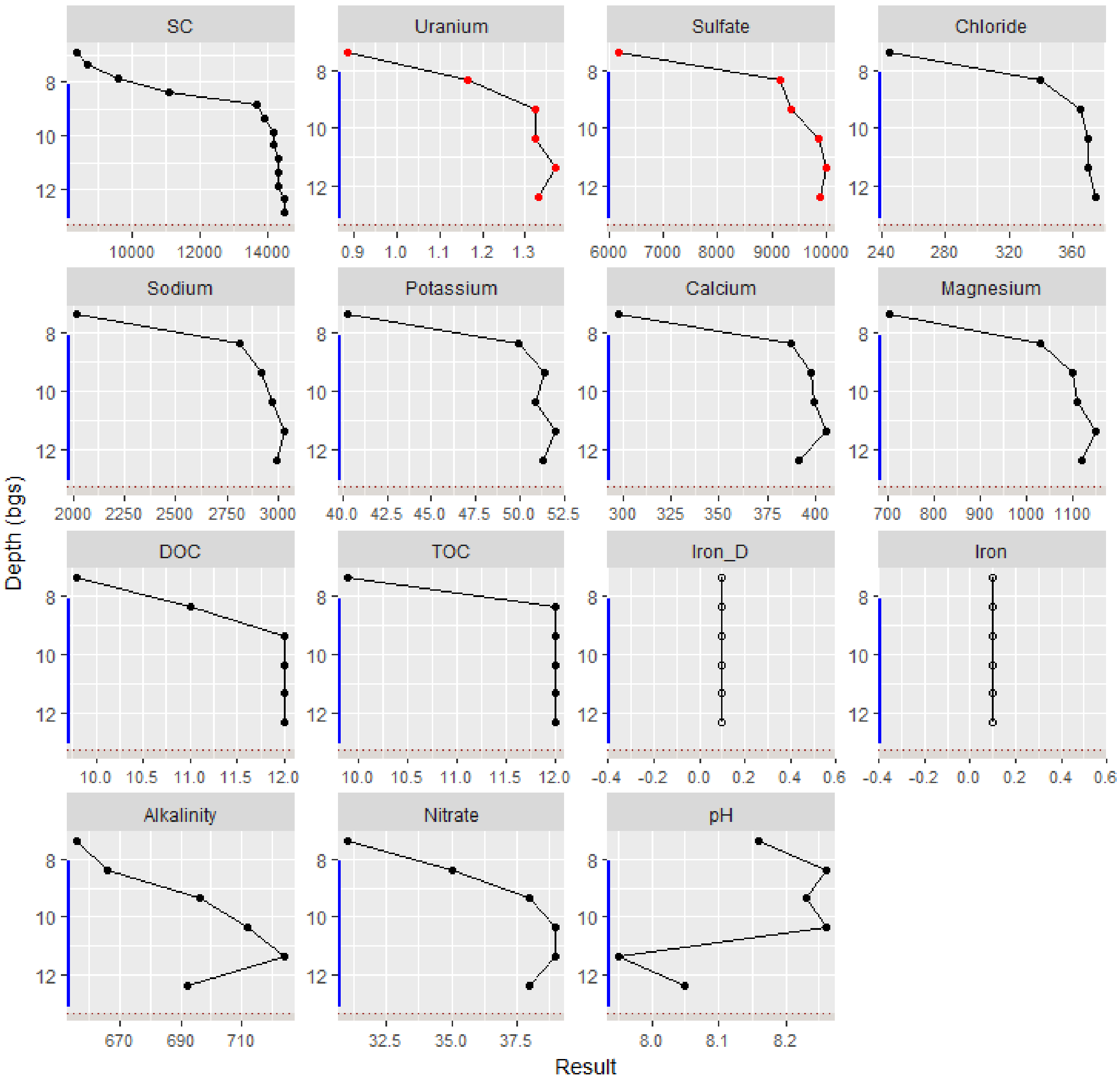


| Screened interval
.... Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level
- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (μS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 1138



| Screened interval

.... Bedrock contact

Mancos Shale

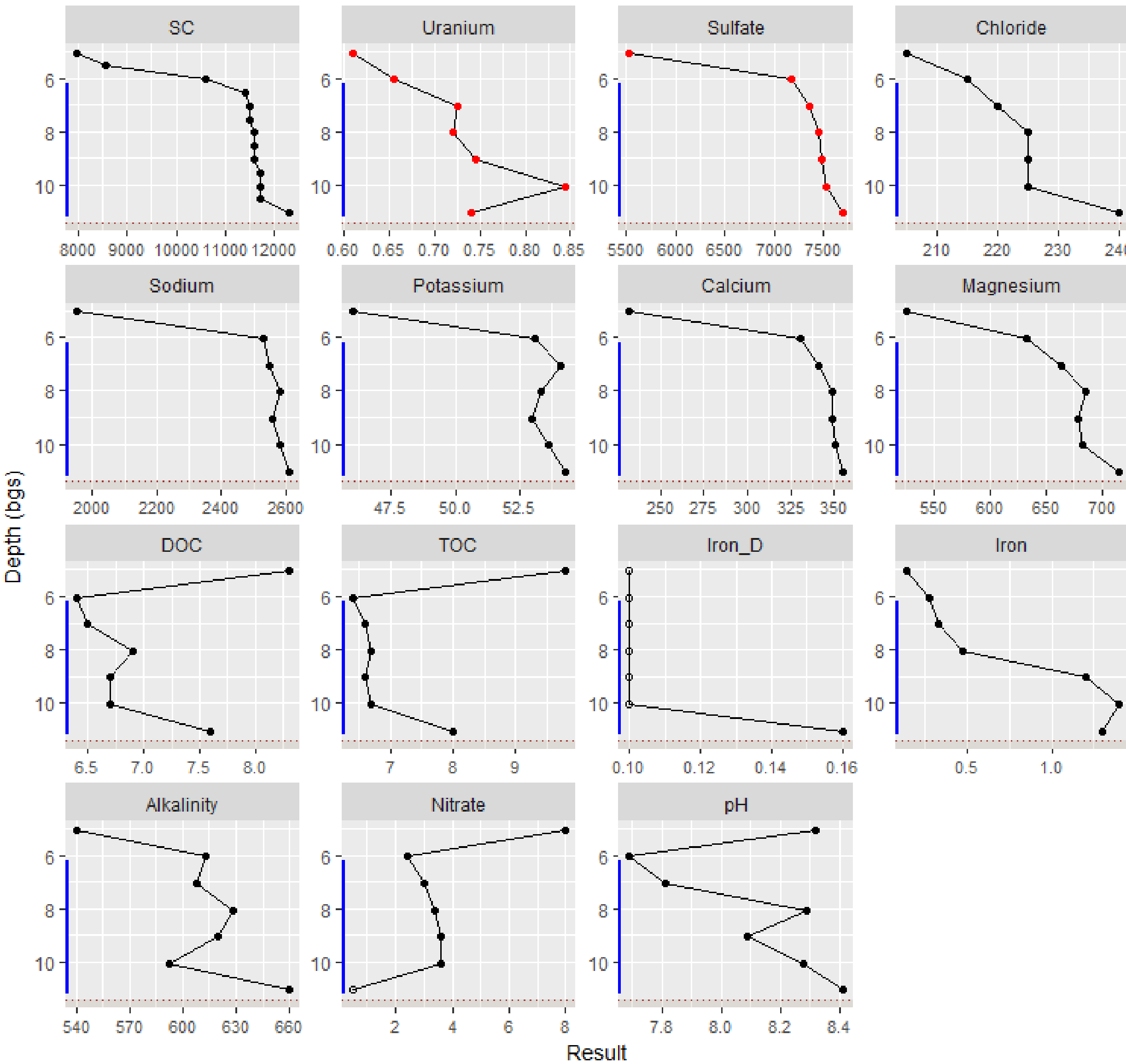
○ BDL result

● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1139



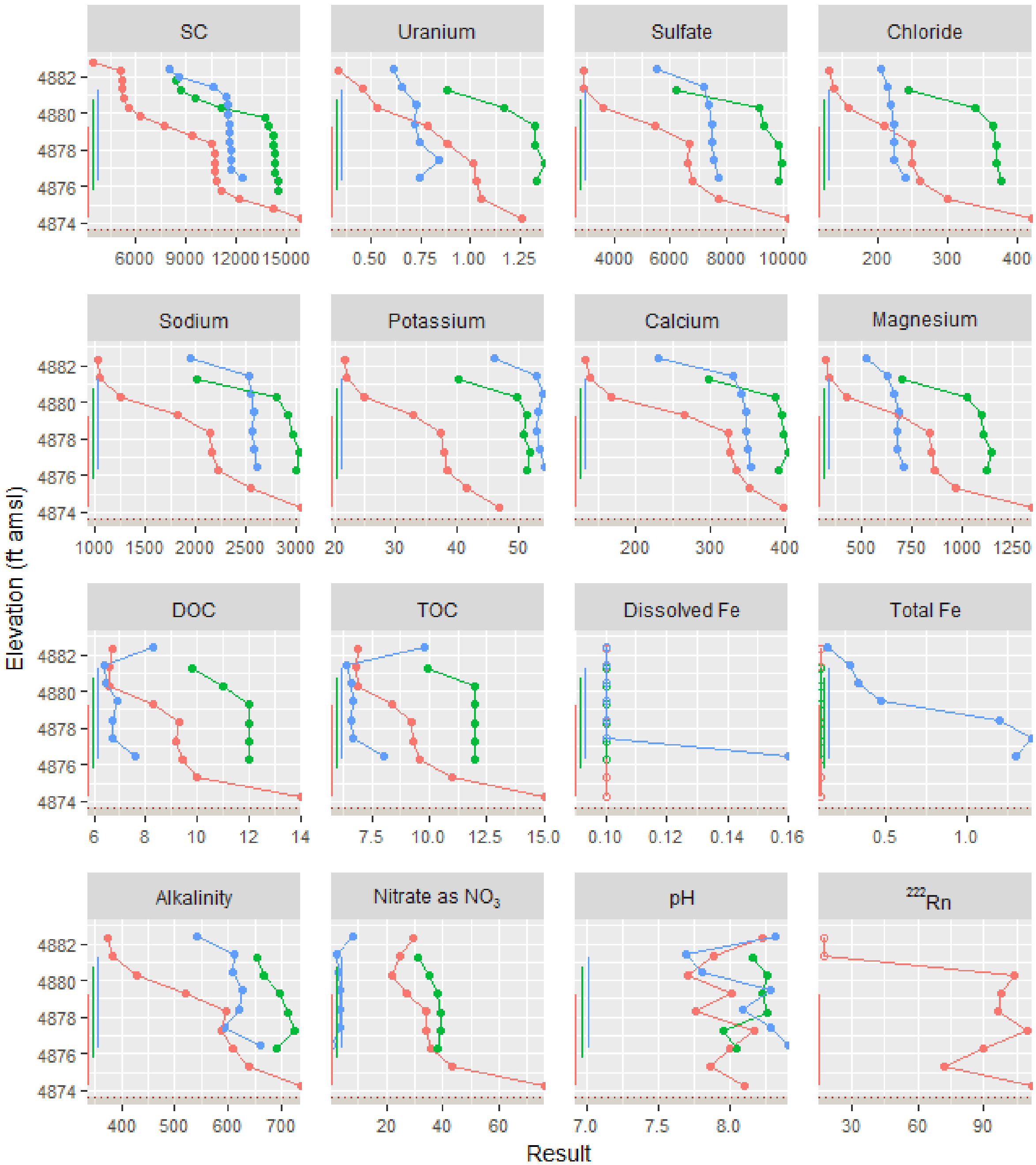
| Screened interval
···· Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Colocated Well Trio:
1137 (orange, closest to San Juan River); 1138 (green); 1139 (blue, closest to pumping area)



| Screened interval

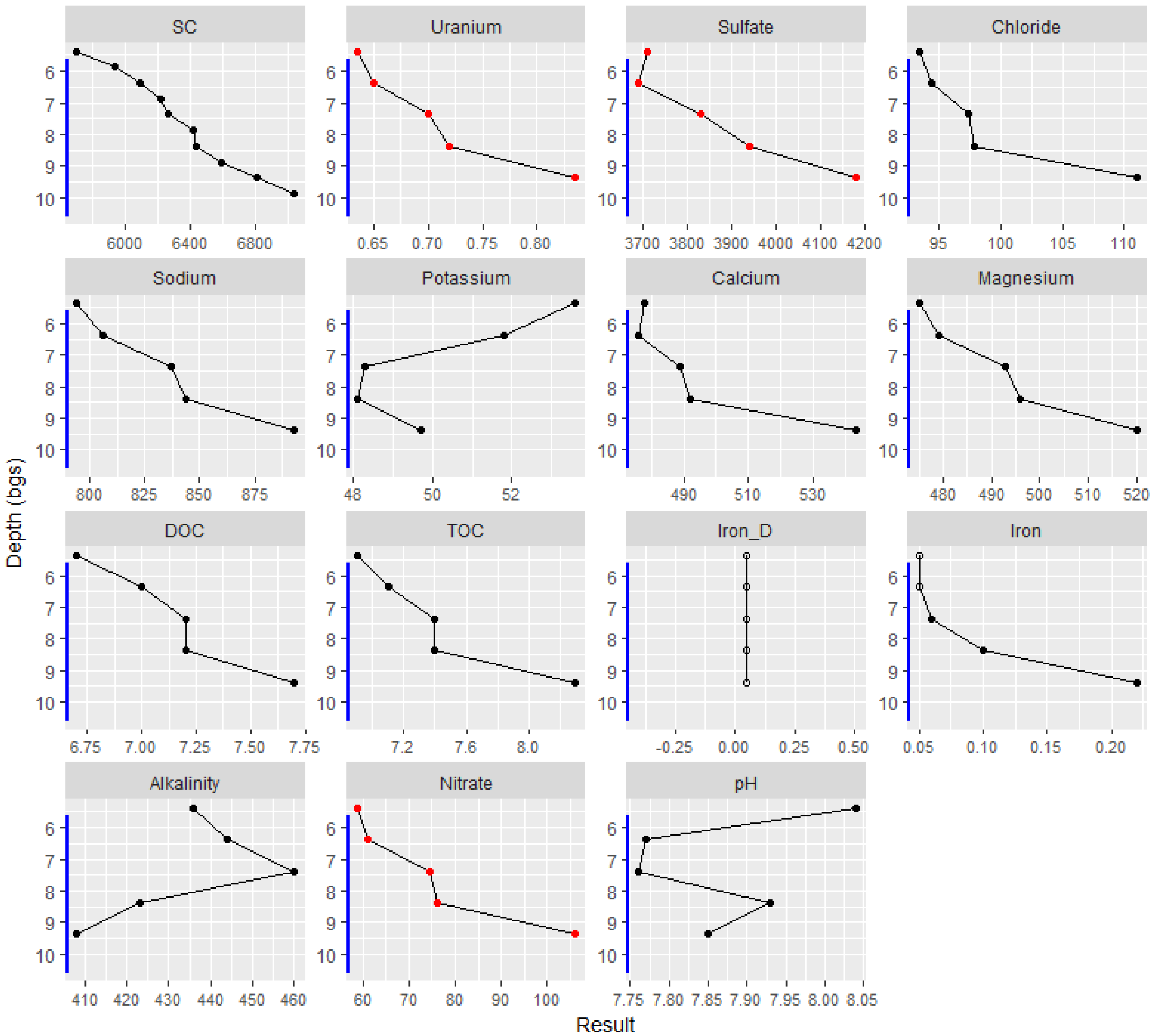
···· Bedrock contact

Mancos Shale

○ BDL result

Note:
All units in mg/L except SC (μS/cm), pH, and ^{222}Rn (pCi/L); alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015
Shiprock Site Floodplain Site Well 1141



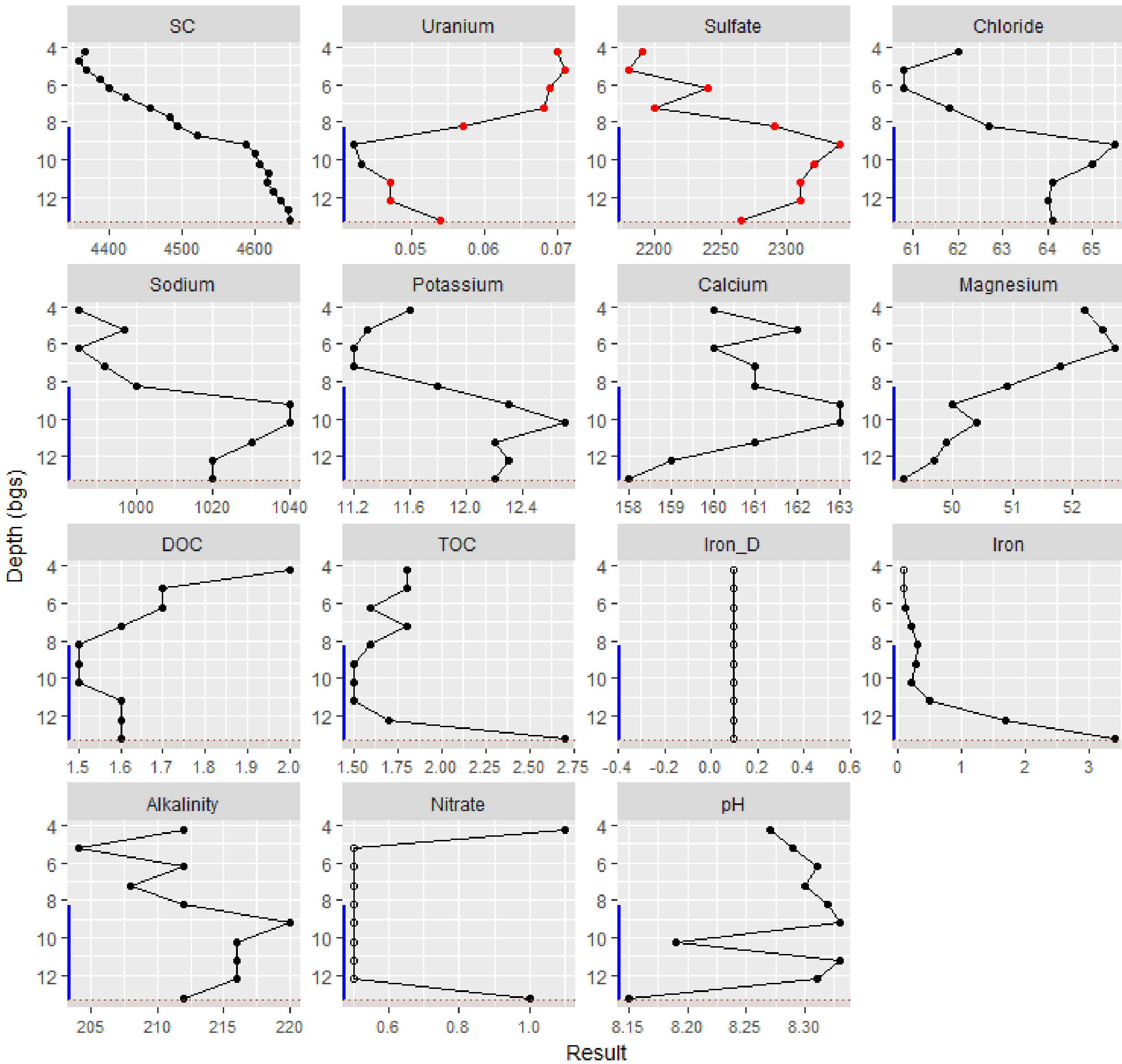
| Screened interval
···· Bedrock contact
Mancos Shale
○ BDL result
● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (µS/cm) and pH; alkalinity as $CaCO_3$.

Phase II SC and Analyte Profile Results: October 2015

Shiprock Site Floodplain Site Well 1143



| Screened interval

···· Bedrock contact

Mancos Shale

○ BDL result

● Result exceeds corresponding 40 CFR 192 MCL or site background level

- 0.044 mg/L uranium
- 2000 mg/L sulfate (background)
- 44 mg/L nitrate as NO_3

Note:
All units in mg/L except SC (μS/cm) and pH; alkalinity as $CaCO_3$.

Appendix F

September 2013 White Paper: Specific Conductivity and Chemical Profiles of Shiprock Floodplain Wells 0857 and 1136–1139: July 2013

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Specific Conductivity and Chemical Profiles of Shiprock Floodplain Wells 0857 and 1136–1139: July 2013

Introduction

This report documents the results of specific conductivity profiles and sampling and analysis of Shiprock central floodplain wells 0857, 1136, 1137, 1138, and 1139 (see map inset below). A catalyst for this effort was observed increases in contaminant concentrations (uranium, sulfate, and nitrate) in these but not other nearby wells. Uranium concentrations in these wells have more than doubled since March 2010 (Exhibit 1). Similar trends are apparent for other contaminants of concern (COCs): sulfate, nitrate and, although low relative to regulatory criteria, selenium. Profiling of nearby well 0618 (about 400 ft west of well 0857) in 2012 and early 2013 indicated vertical stratification in the aquifer in this region. Results of this initial profiling also indicated that some of the variability in historical results could be due to sampling of different strata. To help elucidate the potential causes for the recent increases in the 0857 and 1136–1139 well subset, profiling was conducted in July 2013 as described below.

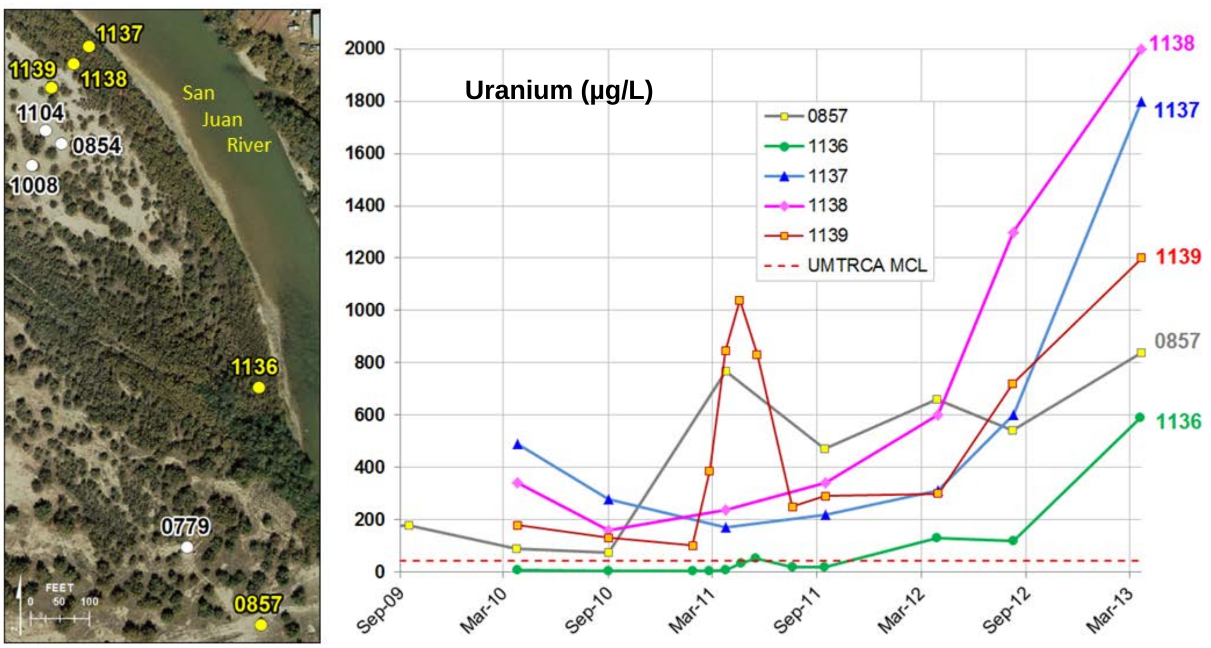


Exhibit 1. Locations and Historical Uranium Results for Shiprock Central Floodplain Well Subset.

Wells profiled in July 2013 are highlighted in the inset map. Recent increases in concentrations shown for uranium are similar in relative magnitude to those observed for other COCs.

Methods

Field work was conducted from July 22 through July 26, 2013. Specific conductivity profiles were run by slowly lowering a sonde (InSitu Troll 200) down the well stopping at each 0.5-foot interval. The sonde was left at the target depth until specific conductivity and temperature readings were stable. Specific conductivity, temperature, time, and depth were recorded at each interval. Each well was developed until the turbidity in the well water was less than 10 NTU, in accordance with standard LM practices. Conductivity profiles and sampling were conducted before and after well development. Samples for chemical analysis were pumped from each 0.5-foot interval (at about 100 - 150 mL/min) as the sample tubing was slowly raised to each target depth. Samples were analyzed in the Environmental Sciences Laboratory for uranium, nitrate, selenium, sulfate, and chloride. Detailed field and laboratory methods are provided at the end of this report.

Results

Figures 1 through 5 plot conductivity and chemical profiles for each well. In these figures, specific conductivity and chemical data are plotted on the upper *x*-axis and elevation on the *y*-axis. The position and length of the well screen is shown next to the *y*-axis. Based on historical practices at LM sites, portions of the well most likely to be sampled (0-2.5 ft from well bottom) are denoted by blue shading. The "a" series of these figures plot only specific conductivity, while the "b" series plots chemical data with the conductivity profiles.

In all "b" series figures, to facilitate review relative to corresponding conductivity profiles, results for all COCs except sulfate are plotted as a multiplier (e.g., 10x, 100x, or 1000x) of the measured value. Unadjusted values are plotted in Figures 6 through 10, which allow comparisons of chemical profiles between wells. The uppermost bars in these figures represent the historical ranges of contaminants color-coded by well. As a summary, Figure 11 shows specific conductivity profiles for all wells based on spatial location. In some cases, figures are followed by a brief caption (in blue font below title) stating a synopsis/interpretation of the plotted data. These figures and the supporting data indicate that:

- For the subset of wells evaluated, stratification (for both conductivity and chemical measurements) appears to be more pronounced in wells 1136 and 0857. Well 1136 shows significant stratification within a small range of depths. Little stratification was observed in wells 1138 and 1139.
- Chemical stratification is most apparent for uranium and sulfate, with the greatest degree apparent in well 1136.
- There are no consistent differences in pre- vs. post-development profiles for this well subset. For the portions of the well most typically sampled (the lowermost 2.5 ft), post-development profiles are generally similar to pre-development profiles.
- Specific conductivities generally increase with increasing depth. For this well subset, conductivities ranged from 1318 microsiemens per centimeter (µS/cm) (uppermost depths of well 1136) to between 18,000 and 20,000 µS/cm in the deeper portion of all wells.

Stratification could be related to a number of factors including: well depths, well construction, proximity to pumped wells, proximity to the river, or saturated thickness. The relationship of well stratification to chemical conditions in the aquifer is a main focus of the ongoing LTSOM variation study.

Figures

Figure List

Abbreviations

amsl	above mean sea level
BTOC	below top of casing
Cl	chloride
DTW	depth to water (as measured from top of casing)
µg/L	micrograms per liter
mg/L	milligrams per liter
Pre-Dev	pre- well development measurement
Post-Dev	post- well development measurement, for this well subset between 54, 55-64 hours after development
Hist	in chemical-specific plots (Figures 6-10), refers to range of historical measurements based on biannual sampling
MCL	maximum concentration limit
µS/cm	microsiemens per centimeter
NO_3	nitrate (as NO_3)
SC	specific conductivity
Se	selenium
SHP	Shiprock
UMTRCA	Uranium Mill Tailings Radiation Control Act

Definition of Terms

Typical Sample Depths – generally, historically taken from within 0 to 2.5 ft from well bottom
“Dead Zone” – area between the bottom of the screened interval and the bottom of well casing

Figure 1a. SHP Well 0857, Specific Conductivity (µS/cm)

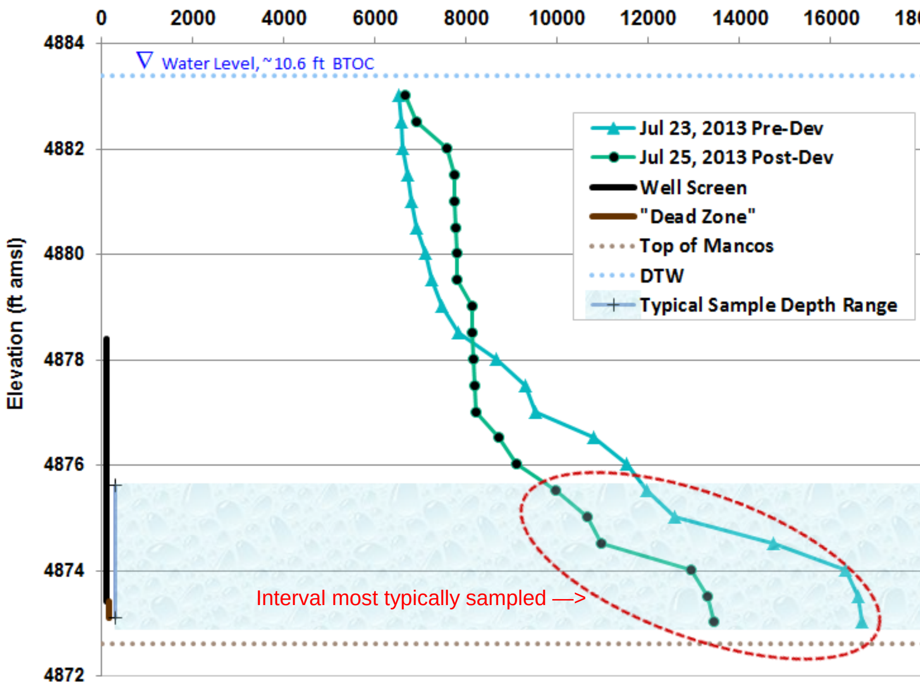


Figure 1b. Specific Conductivity (µS/cm) and Chemical Data Profiles

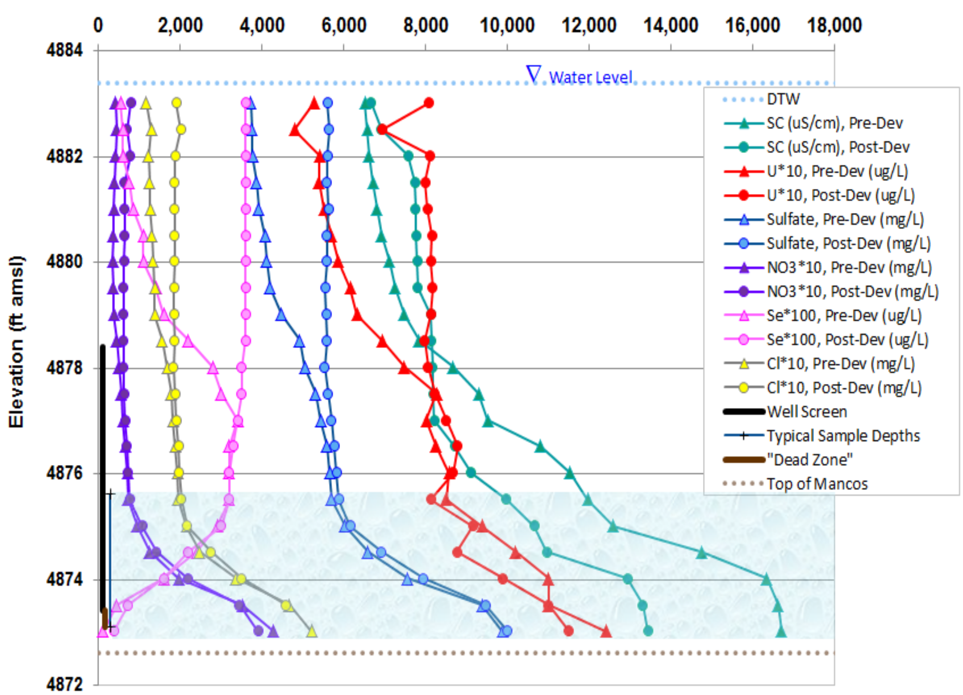


Figure 1. Specific Conductivity and Chemical Profiles for Well 0857, Pre- and Post- Well Development

For both specific conductivity and chemical measurements, stratification is apparent in the lowermost portion of the well. Except for selenium, for which concentrations oddly decrease at lower depths, chemical profiles generally parallel the conductivity profiles.

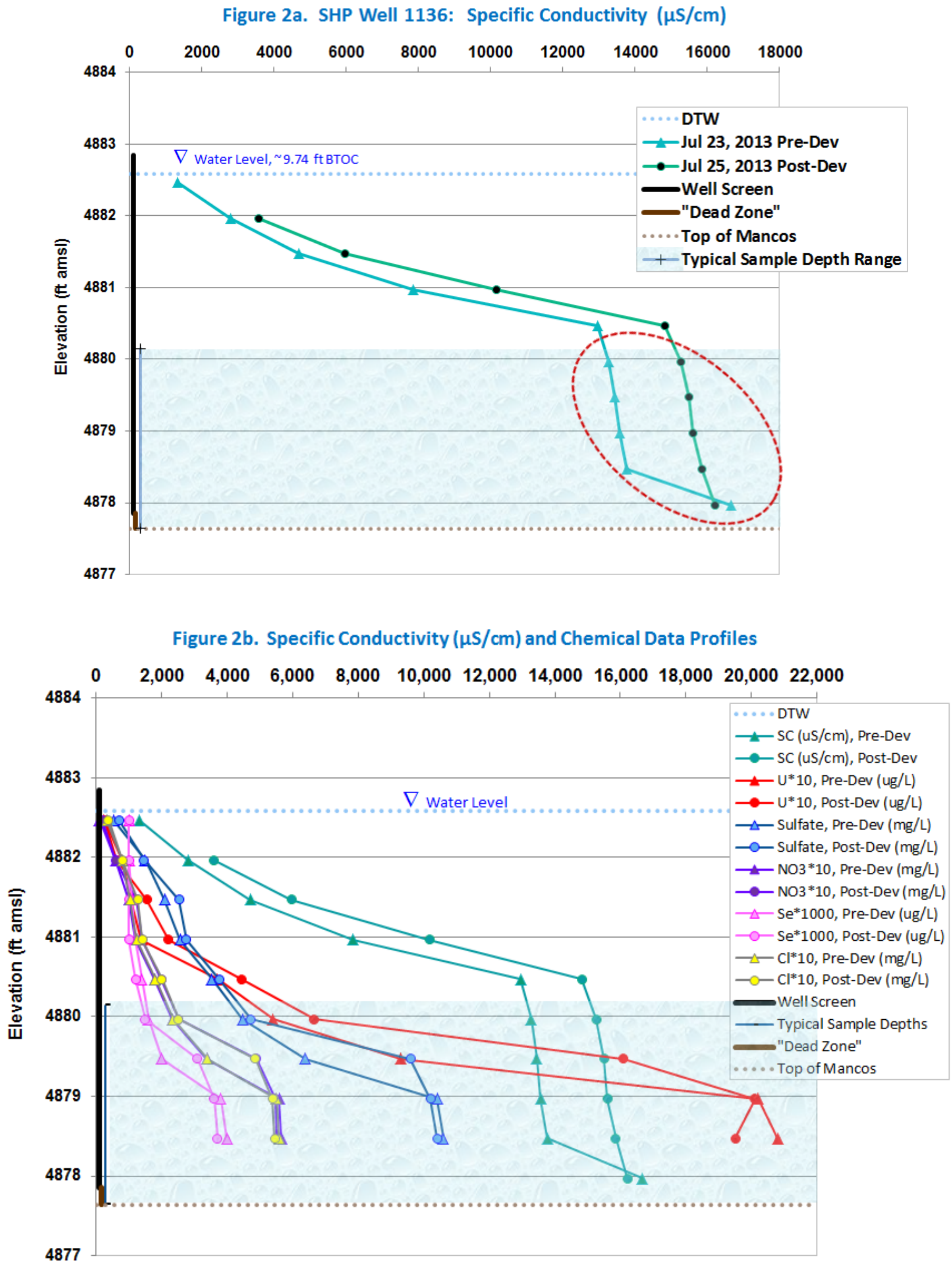
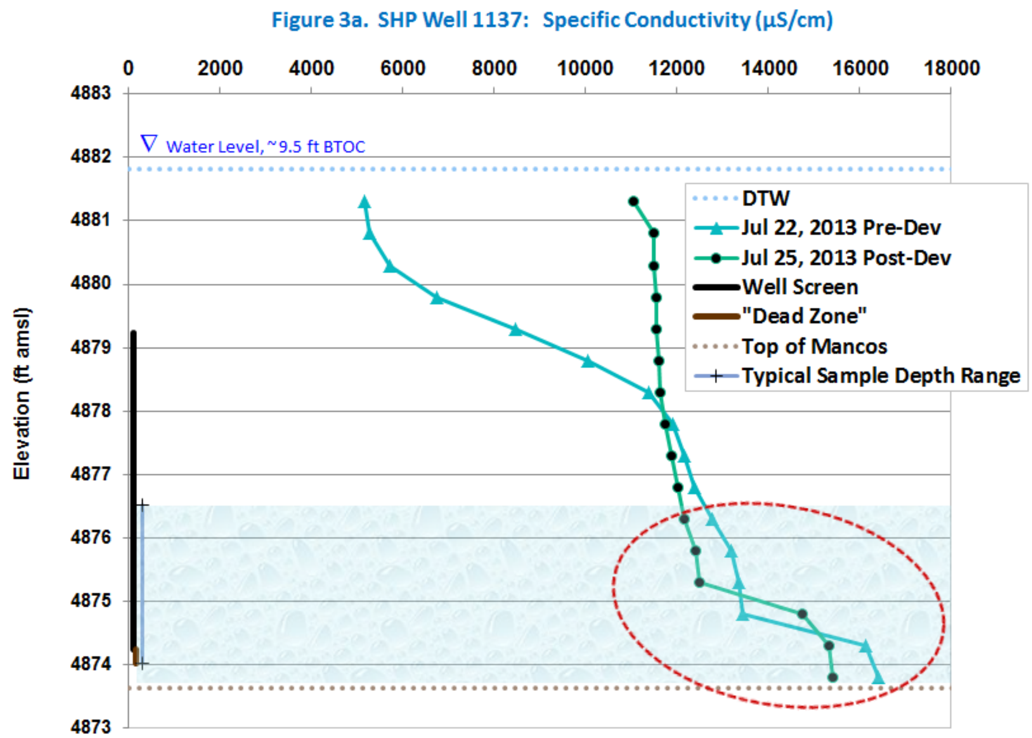


Figure 2. Specific Conductivity and Chemical Profiles for Well 1136, Pre- and Post- Well Development

For both specific conductivity and chemical measurements, vertical stratification is apparent throughout the water column. Stratification is most pronounced for uranium, which increases about 5-fold in the lower half of the screened interval. In Figure 2b, results for all COCs except sulfate are plotted as a multiplier (10x or 1000x) of the measured value; unadjusted values are plotted in Figures 6 through 10.



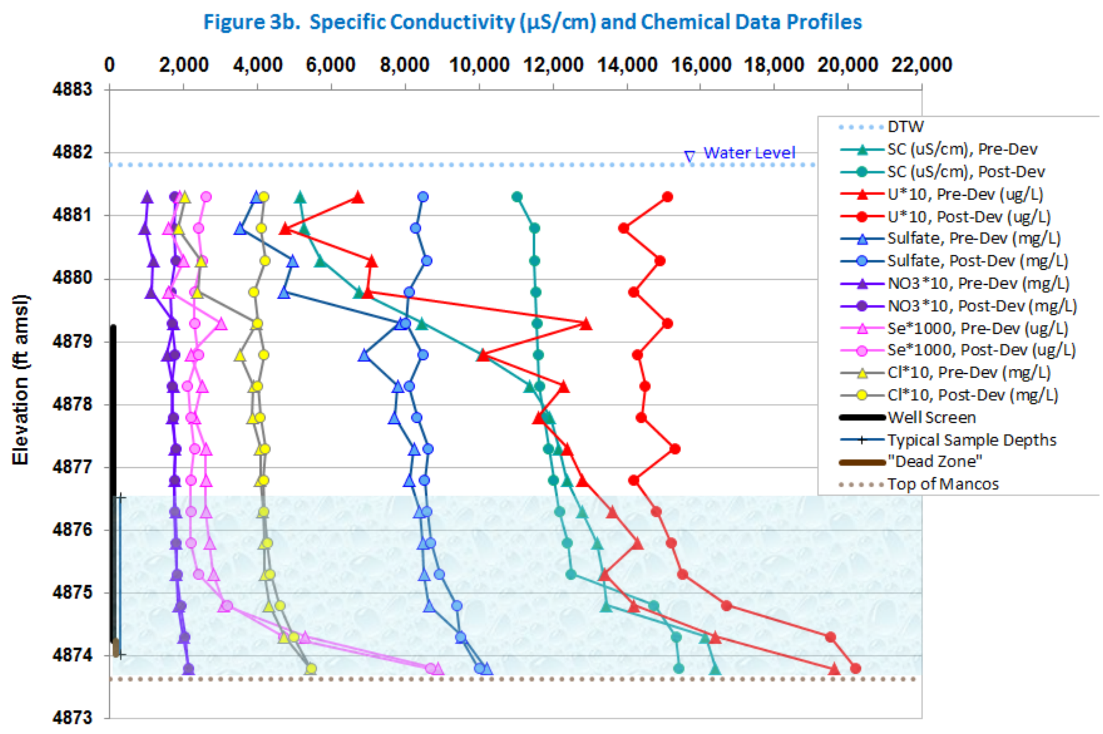


Figure 3. Specific Conductivity and Chemical Profiles for Well 1137, Pre- and Post- Well Development

Pre- and post-development conductivity profiles differ in upper portion of the well. This is also apparent for uranium and to a lesser extent sulfate. Little stratification is apparent for remaining COCs.

Figure 4a. SHP Well 1138: Specific Conductivity (µS/cm)

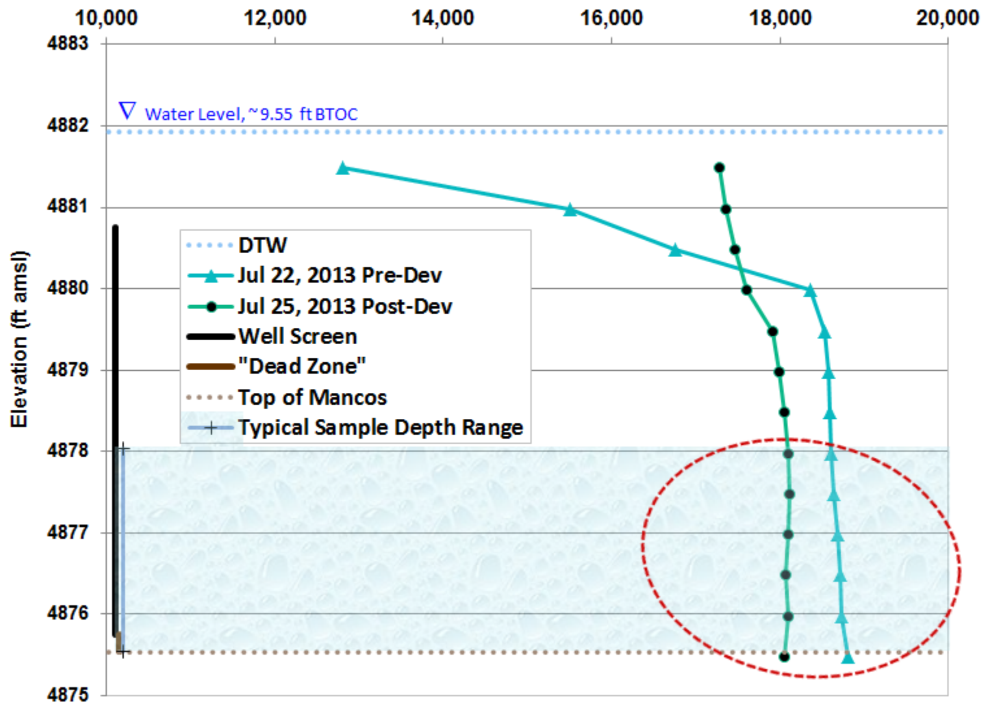


Figure 4b. Specific Conductivity and Chemical Data Profiles

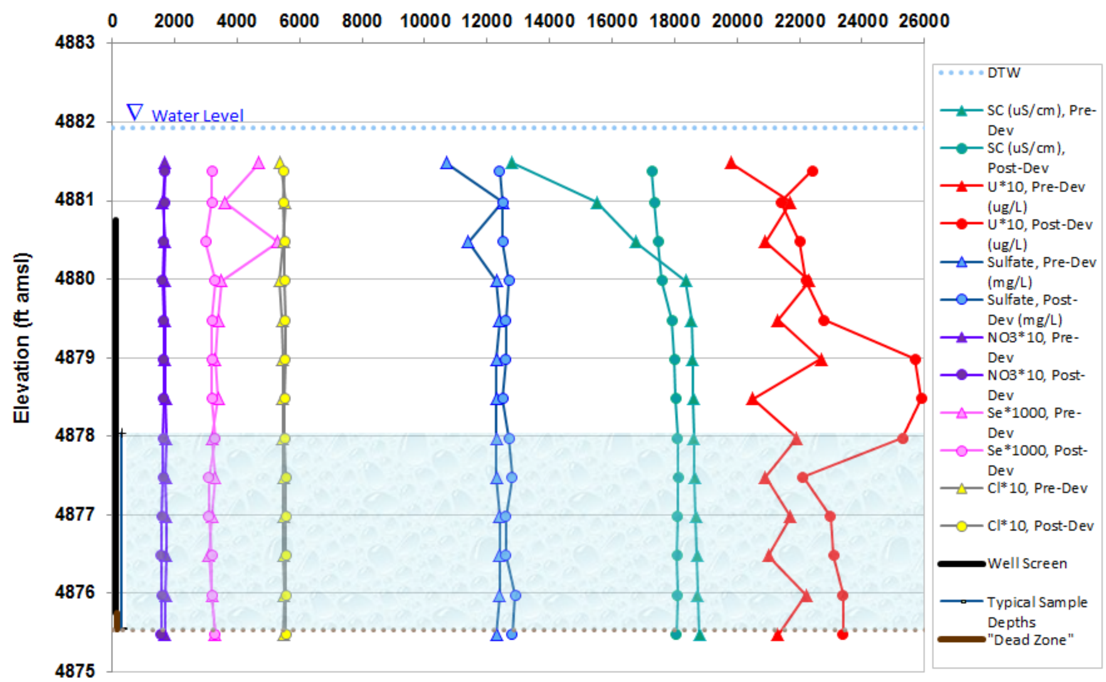
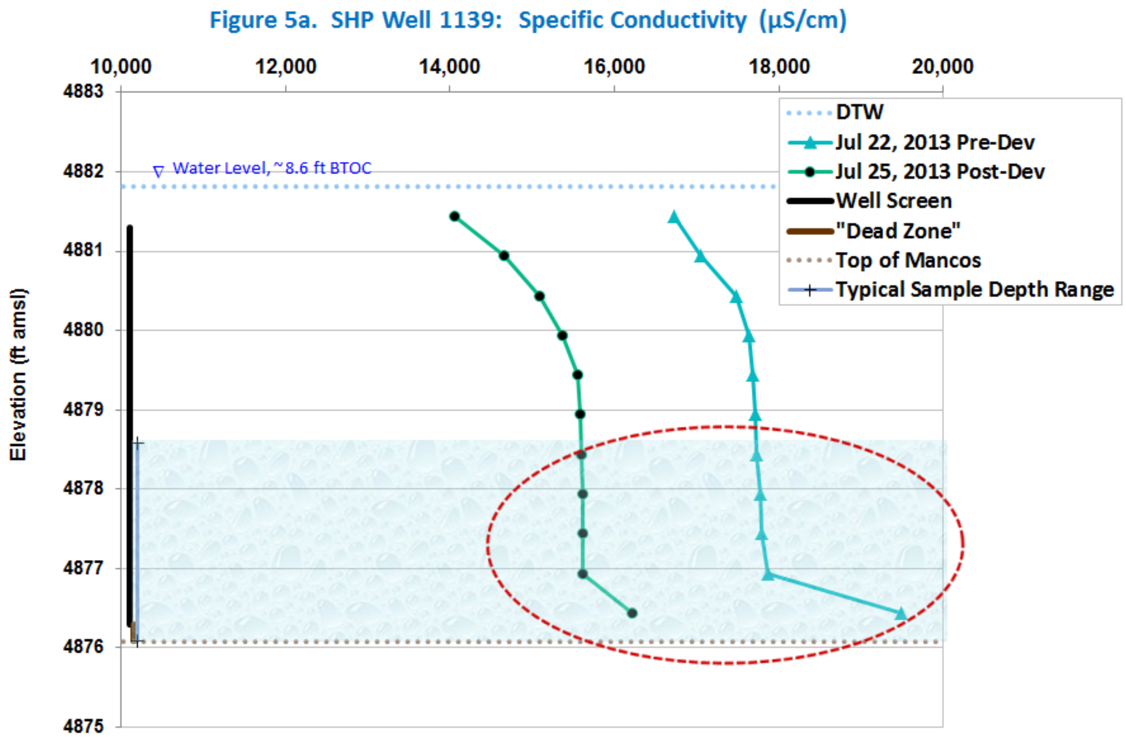


Figure 4. Specific Conductivity and Chemical Profiles for Well 1138, Pre- and Post- Well Development

Except for the pre- well development conductivity profile, well 1138 is not as stratified as most other wells.



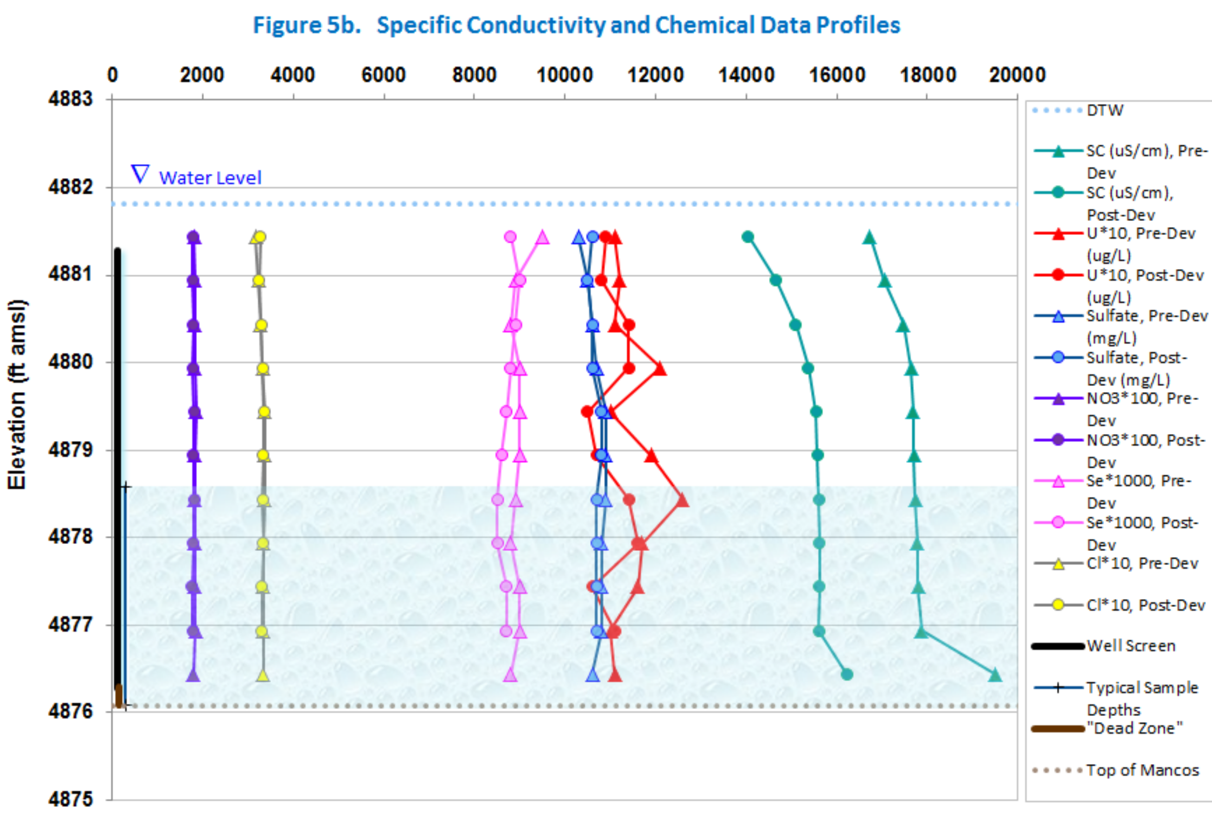


Figure 5. Specific Conductivity and Chemical Profiles for Well 1139, Pre- and Post- Well Development

Similar to the well 1138 profiles (Figure 4), well 1139 is not as stratified as most other wells in this subset.

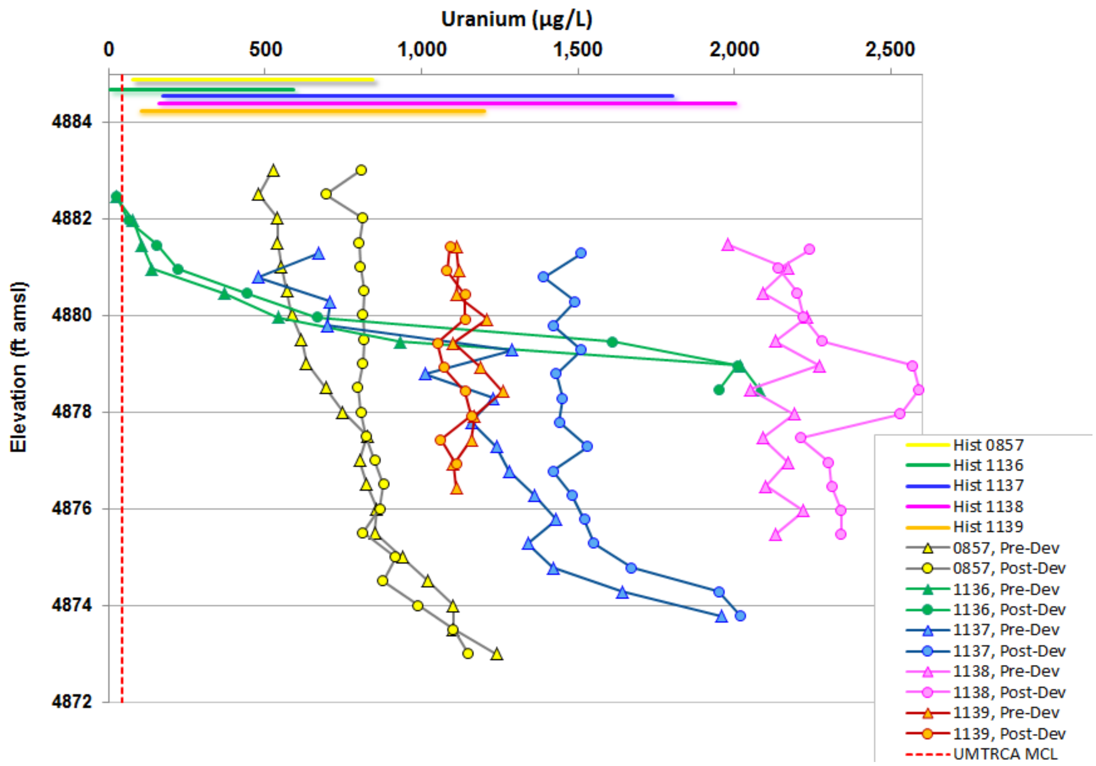


Figure 6. Pre- vs. Post Well Development Profiles for Uranium, All Wells

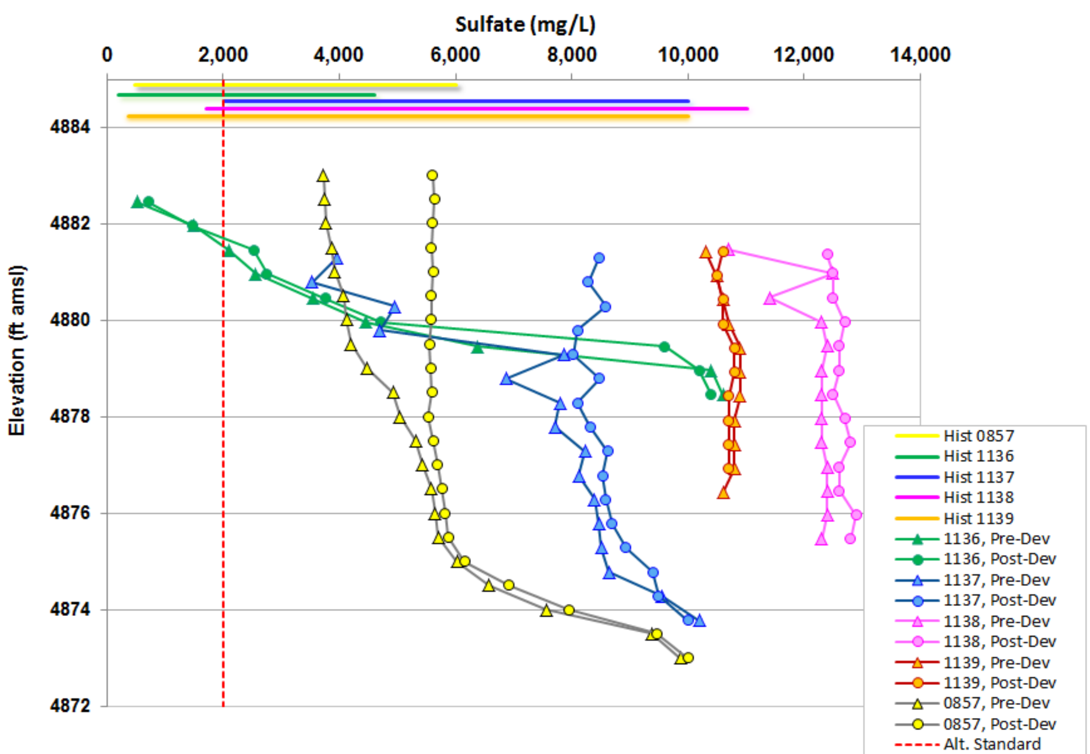


Figure 7. Pre- vs. Post Well Development Profiles for Sulfate, All Wells

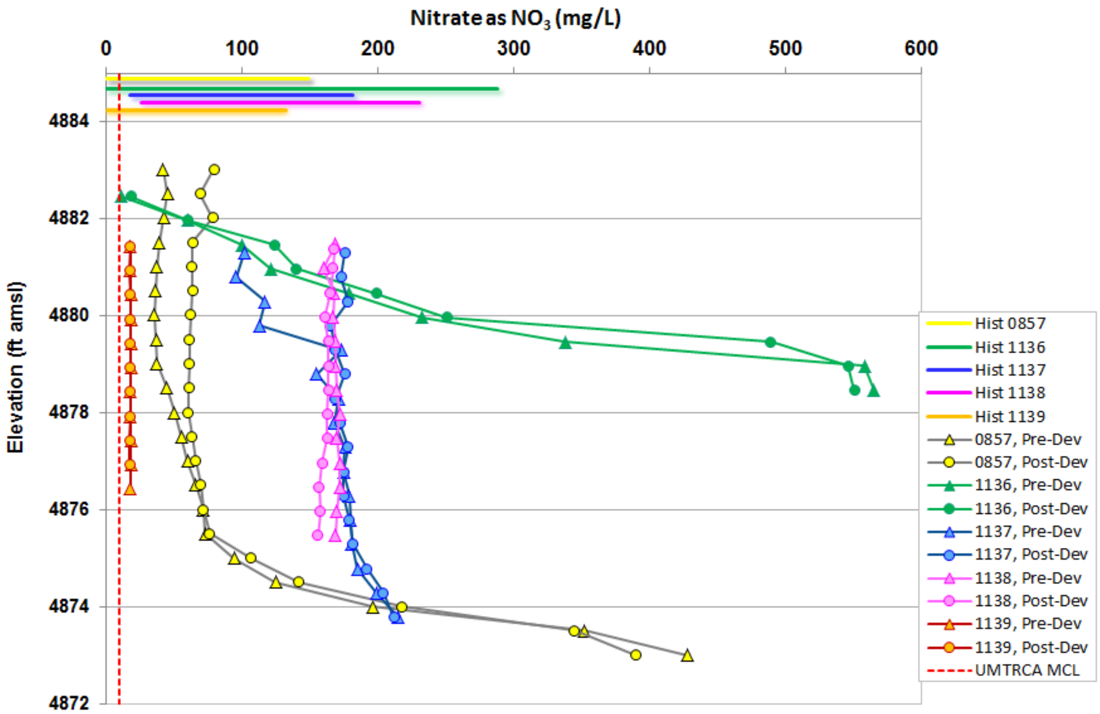


Figure 8. Pre- vs. Post Well Development Profiles for Nitrate as NO_3, All Wells

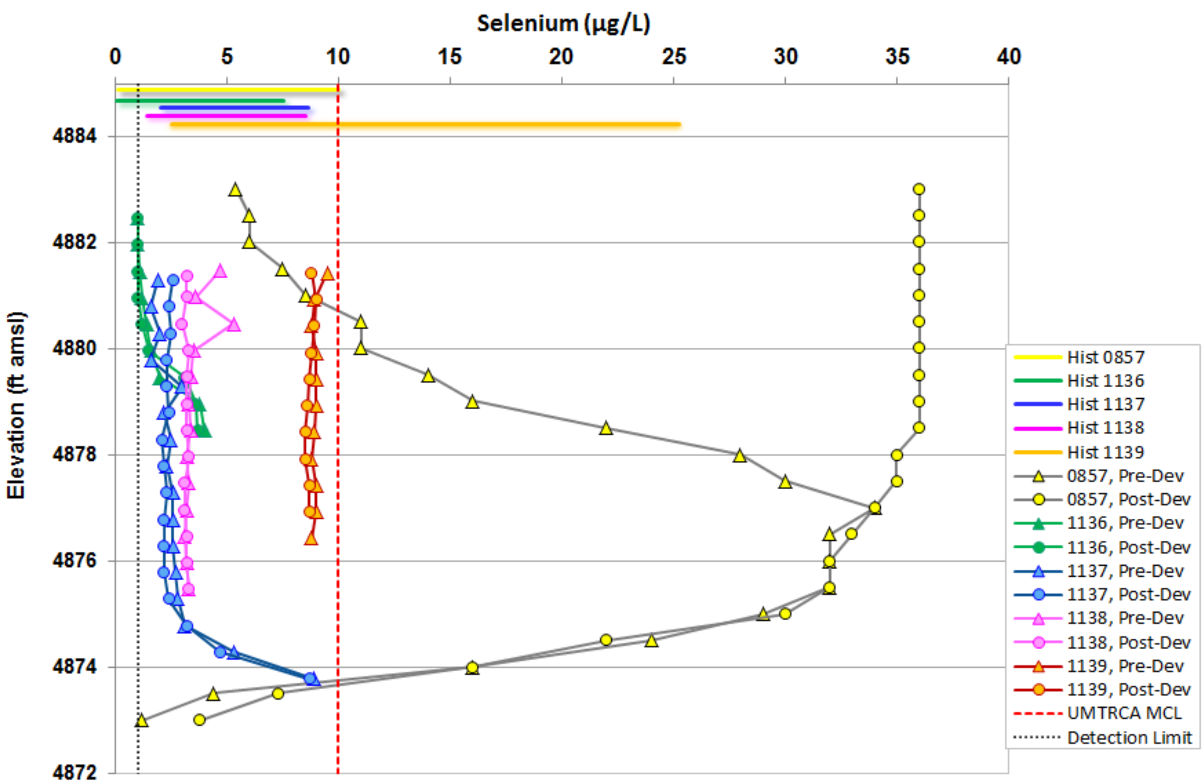


Figure 9. Pre- vs. Post Well Development Profiles for Selenium, All Wells

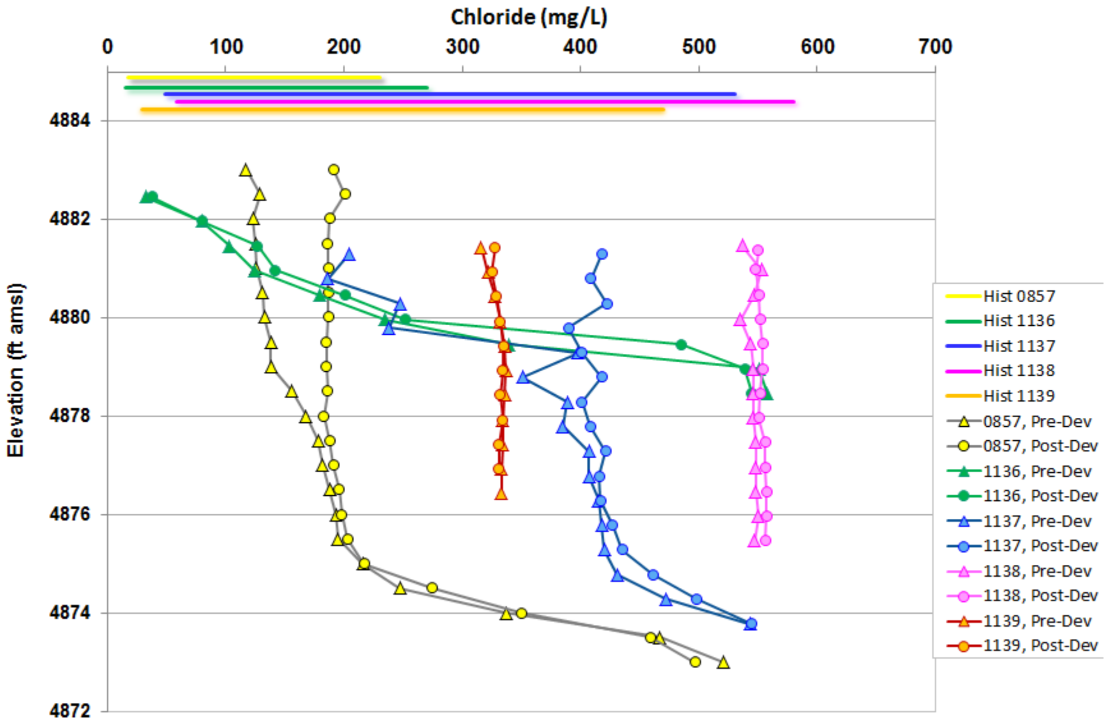
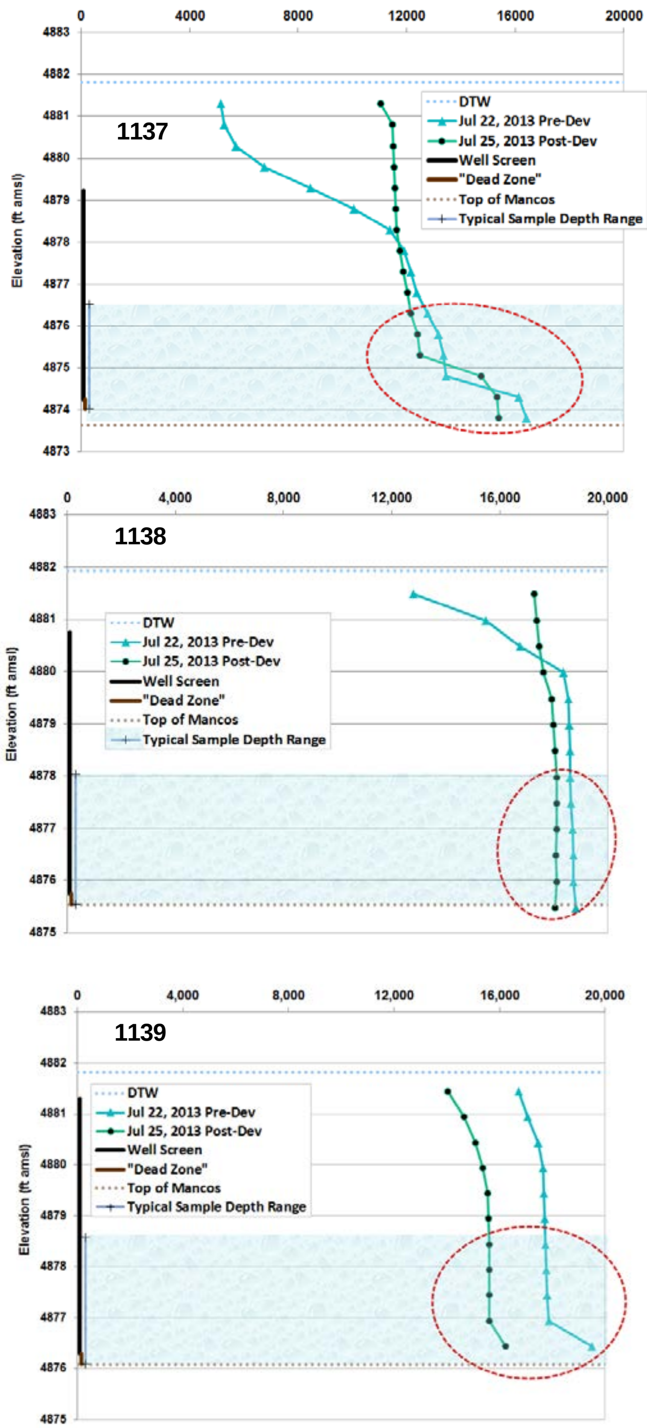
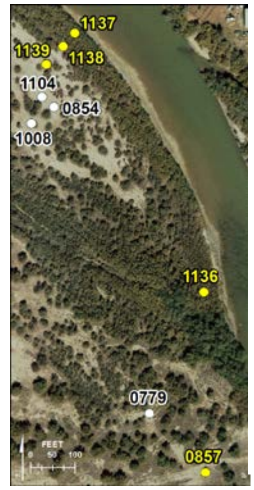


Figure 10. Pre- vs. Post Well Development Profiles for Chloride, All Wells





In this inset, wells in yellow font were evaluated for this study. Wells shown in white, most corresponding to the well 1089/1104 pumping area, are sampled semiannually, but were not profiled.

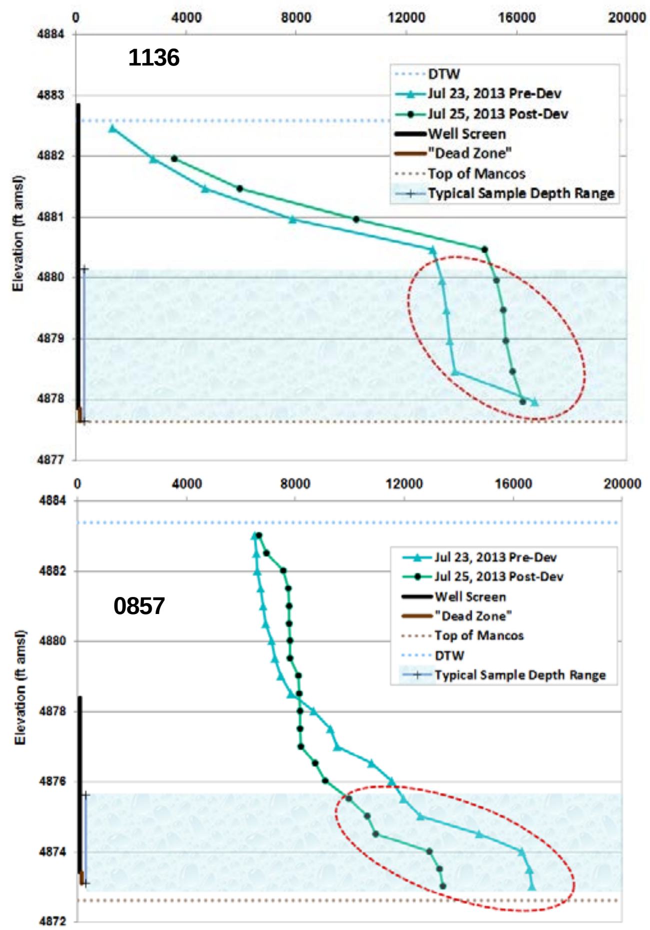


Figure 11. Comparison of Conductivity Profiles Across Well Subset

Wells ordered based on spatial location (see photo inset). Stratification is most pronounced in well 1136, and less pronounced in wells 1138 and 1139.

Methods

Methods

Field work was conducted from July 22 through July 26, 2013. Downhole equipment including sampling tubes and SOARS sensors were removed from each well. Care was taken during equipment removal to minimize disruption to the water column in the well. The wells were allowed to sit, generally overnight, after equipment removal. Profiles were run by slowly lowering a sonde (InSitu Troll 200) down the well stopping at each 0.5-foot interval. The sonde was left at the target depth until the specific conductivity and temperature readings were stable. Specific conductivity, temperature, time, and depth were recorded at each interval. Profiles and sampling were conducted before and after well development.

Sampling was conducted using a peristaltic pump starting near the bottom of the well. Samples were pumped from each 0.5-foot interval as the sample tubing was slowly raised to each target depth. Samples were collected by pumping at about 100 - 150 mL/min. A thin (3/16-inch ID) tube was used to limit disruption to the water column. The thin tube also allowed for a minimal amount of purge between samples. Approximately 100 -200 mL of well water were purged (100 mL minimum) between each sample collection. Samples were not filtered in the field and were collected in 50-mL plastic bottles for transport to the laboratory. Samples were kept cool in an ice chest with blue ice until reaching the laboratory and then were placed in a refrigerator.

Well development followed standard LM procedures. A surge block was used to gently agitate the water column. A peristaltic pump was used to remove water from the well at about 4 to 5 liters per minute. In some wells, the surging and pumping were done several times. Samples were checked for turbidity and the development process was terminated when the turbidity was less than or equal to 10 NTU.

Samples were filtered at the laboratory through 0.45 μM filters. Samples were acidified to a pH value of less than 2 with nitric acid for uranium and selenium analyses. Chloride, sulfate, and nitrate were conducted on filtered, but unacidified splits. Uranium was analyzed by kinetic phosphorescence and selenium by hydride-generation inductively-coupled-plasma optical emission spectrometry. Chloride, sulfate, and nitrate were analyzed by ion chromatography.

Analytical Results

Well	Sample ID	Date	Depth (ft btoc)	Elevation	Sp Cond (µS/cm)	Temp (°C)	Cl (mg/L)	NO_3 mg/L)	SO4 (mg/L)	U (µg/L)	Se (µg/L)
857	857-11	7/23/2013	11	4883.0	6522	19.33	117	42.2	3720	526	5.4
857	857.11.5	7/23/2013	11.5	4882.5	6568	18.73	129	45.2	3750	479	6.0
857	857-12	7/23/2013	12	4882.0	6606	18.4	123	42.4	3770	540	6.0
857	857-12.5	7/23/2013	12.5	4881.5	6715	17.96	125	39.4	3860	539	7.5
857	857-13	7/23/2013	13	4881.0	6811	17.72	126	37.6	3920	551	8.5
857	857-13.5	7/23/2013	13.5	4880.5	6912	17.49	131	36.5	4070	569	11
857	857-14	7/23/2013	14	4880.0	7117	17.22	133	35.4	4120	586	11
857	857-14.5	7/23/2013	14.5	4879.5	7253	17.04	138	36.9	4200	616	14
857	857-15	7/23/2013	15	4879.0	7467	16.85	138	37.5	4470	632	16
857	857-15.5	7/23/2013	15.5	4878.5	7830	16.68	156	44.6	4920	693	22
857	857-16	7/23/2013	16	4878.0	8671	16.51	168	50.6	5040	748	28
857	857-16.5	7/23/2013	16.5	4877.5	9299	16.35	178	55.4	5310	827	30
857	857-17	7/23/2013	17	4877.0	9517	16.14	182	60.2	5430	802	34
857	857-17.5	7/23/2013	17.5	4876.5	10809	16	188	66.1	5580	825	32
857	857-18	7/23/2013	18	4876.0	11528	15.88	193	71.7	5650	857	32
857	857-18.5	7/23/2013	18.5	4875.5	11963	15.77	195	73.1	5700	850	32
857	857-19	7/23/2013	19	4875.0	12579	15.6	216	94.4	6030	938	29
857	857-19.5	7/23/2013	19.5	4874.5	14733	15.49	247	125	6580	1020	24
857	857-20	7/23/2013	20	4874.0	16329	15.43	337	196	7560	1100	16
857	857-20.5	7/23/2013	20.5	4873.5	16605	15.36	467	352	9370	1100	4.4
857	857-21	7/23/2013	21	4873.0	16694	15.3	521	428	9870	1240	1.2
857	857-11	7/26/2013	11	4883.0	6671	22.61	191	79.4	5600	807	36
857	857.11.5	7/26/2013	11.5	4882.5	6924	21.2	201	69.2	5640	693	36
857	857-12	7/26/2013	12	4882.0	7566	18.14	188	78.6	5600	811.1	36
857	857-12.5	7/26/2013	12.5	4881.5	7740	18.07	186	63.6	5580	799	36
857	857-13	7/26/2013	13	4881.0	7757	17.93	187	63.5	5620	804	36
857	857-13.5	7/26/2013	13.5	4880.5	7759	17.78	187	63.6	5580	816	36
857	857-14	7/26/2013	14	4880.0	7789	17.56	187	62.3	5580	812	36
857	857-14.5	7/26/2013	14.5	4879.5	7809	17.39	185	61.7	5550	816	36
857	857-15	7/26/2013	15	4879.0	8124	17.2	185	61.4	5570	813	36
857	857-15.5	7/26/2013	15.5	4878.5	8146	17.02	186	61	5590	797	36
857	857-16	7/26/2013	16	4878.0	8164	16.85	183	60.8	5530	806	35
857	857-16.5	7/26/2013	16.5	4877.5	8181	16.69	188	63.3	5610	822	35
857	857-17	7/26/2013	17	4877.0	8210	16.54	191	65.9	5690	850	34
857	857-17.5	7/26/2013	17.5	4876.5	8714	16.36	196	69.8	5770	878	33
857	857-18	7/26/2013	18	4876.0	9113	16.16	198	71.9	5820	867	32
857	857-18.5	7/26/2013	18.5	4875.5	9975	15.98	203	76.3	5870	813	32
857	857-19	7/26/2013	19	4875.0	10657	15.86	217	107	6160	916	30
857	857-19.5	7/26/2013	19.5	4874.5	10961	15.75	275	142	6920	876	22
857	857-20	7/26/2013	20	4874.0	12930	15.64	350	218	7950	990	16
857	857-20.5	7/26/2013	20.5	4873.5	13310	15.56	459	345	9460	1100	7.3
857	857-21	7/26/2013	21	4873.0	13427	15.45	497	390	10000	1150	3.8
1136	1136-10	7/23/2013	10	4882.5	1318	19.56	32.2	11.3	522	24.7	**1**
1136	1136-10.5	7/23/2013	10.5	4882.0	2810	17.15	79.8	60	1500	78.7	**1**
1136	1136-11	7/23/2013	11	4881.5	4699	16.3	103	100	2090	107	1.1
1136	1136-11.5	7/23/2013	11.5	4881.0	7852	15.76	124	121	2560	139	1.2
1136	1136-12	7/23/2013	12	4880.5	12954	15.27	180	179	3540	370	1.4
1136	1136-12.5	7/23/2013	12.5	4880.0	13281	14.91	235	233	4460	541	1.6
1136	1136-13	7/23/2013	13	4879.5	13442	14.73	339	338	6380	931	2
1136	1136-13.5	7/23/2013	13.5	4879.0	13567	14.59	551	558	10400	2020	3.8

Well	Sample ID	Date	Depth (ft btoc)	Elevation	Sp Cond (µS/cm)	Temp (°C)	Cl (mg/L)	NO_3 mg/L)	SO4 (mg/L)	U (µg/L)	Se (µg/L)
1136	1136-14	7/23/2013	14	4878.5	13765	14.42	558	565	10600	2080	4.0
1136	1136-14.5	7/23/2013	14.5	4878.0	16673	14.19	NS	NS	NS	NS	NS
1136	1136-10.1	7/26/2013	10.1	4882.5			37.7	18.4	707	25.5	**1**
1136	1136-10.5	7/26/2013	10.5	4882.0	3578	19.07	80.1	60.4	1470	62.9	**1**
1136	1136-11	7/26/2013	11	4881.5	5960	17.43	127	124	2530	154	**1**
1136	1136-11.5	7/26/2013	11.5	4881.0	10171	16.55	142	140	2750	220	1.0
1136	1136-12	7/26/2013	12	4880.5	14829	16.04	201	199	3760	443	1.2
1136	1136-12.5	7/26/2013	12.5	4880.0	15263	15.62	252	251	4720	665	1.5
1136	1136-13	7/26/2013	13	4879.5	15507	15.19	485	489	9600	1610	3.1
1136	1136-13.5	7/26/2013	13.5	4879.0	15604	14.96	539	546	10200	2010	3.6
1136	1136-14	7/26/2013	14	4878.5	15853	14.69	545	551	10400	1950	3.7
1136	1136-14.5	7/26/2013	14.2	4878.3	16214	14.56	NS	NS	NS	NS	NS
1137	1137-10	7/23/2013	10	4881.3	5151	14.52	204	102	3950	670	1.9
1137	1137-10.5	7/23/2013	10.5	4880.8	5272	14.1	186	95.6	3530	476	1.6
1137	1137-11	7/23/2013	11	4880.3	5714	13.82	247	117	4960	709	2.0
1137	1137-11.5	7/23/2013	11.5	4879.8	6739	13.51	238	113	4700	698	1.6
1137	1137-12	7/23/2013	12	4879.3	8462	13.29	398	173	7860	1290	3.0
1137	1137-12.5	7/23/2013	12.5	4878.8	10061	13.12	351	155	6870	1010	2.2
1137	1137-13	7/23/2013	13	4878.3	11376	13.01	389	171	7800	1230	2.5
1137	1137-13.5	7/23/2013	13.5	4877.8	11915	12.88	385	168	7710	1160	2.3
1137	1137-14	7/23/2013	14	4877.3	12150	12.8	407	176	8230	1240	2.6
1137	1137-14.5	7/23/2013	14.5	4876.8	12371	12.73	407	175	8120	1280	2.6
1137	1137-15	7/23/2013	15	4876.3	12782	12.64	415	179	8390	1360	2.6
1137	1137-15.5	7/23/2013	15.5	4875.8	13185	12.53	418	180	8470	1430	2.7
1137	1137-16	7/23/2013	16	4875.3	13360	12.42	420	181	8510	1340	2.8
1137	1137-16.5	7/23/2013	16.5	4874.8	13446	12.3	431	185	8640	1420	3.1
1137	1137-17	7/23/2013	17	4874.3	16124	12.07	472	199	9550	1640	5.3
1137	1137-17.5	7/23/2013	17.5	4873.8	16398	11.98	543	215	10200	1960	8.9
1137	1137-10	7/25/2013	10	4881.3	11037	17.95	418	176	8470	1510	2.6
1137	1137-10.5	7/25/2013	10.5	4880.8	11488	14.59	409	173	8280	1390	2.4
1137	1137-11	7/25/2013	11	4880.3	11497	14.26	422	178	8580	1490	2.5
1137	1137-11.5	7/25/2013	11.5	4879.8	11536	14	390	165	8100	1420	2.3
1137	1137-12	7/25/2013	12	4879.3	11561	13.79	401	169	8020	1510	2.3
1137	1137-12.5	7/25/2013	12.5	4878.8	11602	13.55	418	176	8480	1430	2.4
1137	1137-13	7/25/2013	13	4878.3	11629	13.4	401	169	8100	1450	2.1
1137	1137-13.5	7/25/2013	13.5	4877.8	11754	13.26	408	172	8320	1440	2.2
1137	1137-14	7/25/2013	14	4877.3	11883	13.11	421	178	8620	1530	2.3
1137	1137-14.5	7/25/2013	14.5	4876.8	12024	12.97	416	175	8530	1420	2.2
1137	1137-15	7/25/2013	15	4876.3	12166	12.86	417	175	8590	1480	2.2
1137	1137-15.5	7/25/2013	15.5	4875.8	12397	12.76	427	179	8690	1520	2.2
1137	1137-16	7/25/2013	16	4875.3	12491	12.62	435	182	8930	1550	2.4
1137	1137-16.5	7/25/2013	16.5	4874.8	14739	12.36	461	192	9390	1670	3.2
1137	1137-17	7/25/2013	17	4874.3	15327	12.25	498	204	9490	1950	4.7
1137	1137-17.5	7/25/2013	17.5	4873.8	15409	12.14	545	212	10000	2020	8.7
1138	1138-10	7/23/2013	10	4881.5	12806	17.95	537	169	10700	1980	4.7
1138	1138-10.5	7/23/2013	10.5	4881.0	15500	16.84	553	160	12500	2170	3.6
1138	1138-11	7/23/2013	11	4880.5	16760	16.29	547	168	11400	2090	5.3
1138	1138-11.5	7/23/2013	11.5	4880.0	18356	15.74	535	167	12300	2230	3.5
1138	1138-12	7/23/2013	12	4879.5	18537	15.46	544	169	12400	2130	3.4

Well	Sample ID	Date	Depth (ft btoc)	Elevation	Sp Cond (µS/cm)	Temp (°C)	Cl (mg/L)	NO_3 mg/L)	SO4 (mg/L)	U (µg/L)	Se (µg/L)
1138	1138-12.5	7/23/2013	12.5	4879.0	18577	15.29	546	169	12300	2270	3.3
1138	1138-13	7/23/2013	13	4878.5	18596	15.2	546	170	12300	2050	3.4
1138	1138-13.5	7/23/2013	13.5	4878.0	18610	15.09	546	172	12300	2190	3.2
1138	1138-14	7/23/2013	14	4877.5	18636	14.91	548	170	12300	2090	3.3
1138	1138-14.5	7/23/2013	14.5	4877.0	18684	14.77	548	172	12400	2170	3.2
1138	1138-15	7/23/2013	15	4876.5	18715	14.66	548	172	12400	2100	3.1
1138	1138-15.5	7/23/2013	15.5	4876.0	18736	14.55	550	170	12400	2220	3.2
1138	1138-16	7/23/2013	16	4875.5	18809	14.27	547	169	12300	2130	3.3
1138	1138-10.1	7/25/2013	10.1	4881.4	17283	18.83	550	168	12400	2240	3.2
1138	1138-10.5	7/25/2013	10.5	4881.0	17359	18.09	548	167	12500	2140	3.2
1138	1138-11	7/25/2013	11	4880.5	17469	17.41	551	165	12500	2200	3.0
1138	1138-11.5	7/25/2013	11.5	4880.0	17605	16.87	552	161	12700	2220	3.3
1138	1138-12	7/25/2013	12	4879.5	17911	16.23	554	164	12600	2280	3.2
1138	1138-12.5	7/25/2013	12.5	4879.0	17992	15.89	554	164	12600	2570	3.2
1138	1138-13	7/25/2013	13	4878.5	18046	15.68	552	164	12500	2590	3.2
1138	1138-13.5	7/25/2013	13.5	4878.0	18106	15.53	551	163	12700	2530	3.3
1138	1138-14	7/25/2013	14	4877.5	18108	15.34	556	163	12800	2210	3.1
1138	1138-14.5	7/25/2013	14.5	4877.0	18097	15.13	556	159	12600	2300	3.1
1138	1138-15	7/25/2013	15	4876.5	18069	14.97	557	157	12600	2310	3.2
1138	1138-15.5	7/25/2013	15.5	4876.0	18098	14.77	557	158	12900	2340	3.2
1138	1138-16	7/25/2013	16	4875.5	18055	14.51	556	156	12800	2340	3.3
1139	1139-9	7/23/2013	9	4881.4	16728	22.16	316	18.1	10300	1110	9.5
1139	1139-9.5	7/23/2013	9.5	4880.9	17047	21.15	322	18.2	10500	1120	8.9
1139	1139-10	7/23/2013	10	4880.4	17475	20.68	328	18.3	10600	1110	8.8
1139	1139-10.5	7/23/2013	10.5	4879.9	17642	20.21	332	18.3	10700	1210	9.0
1139	1139-11	7/23/2013	11	4879.4	17684	19.97	336	18.5	10900	1100	9.0
1139	1139-11.5	7/23/2013	11.5	4878.9	17706	19.71	337	18.3	10900	1190	9.0
1139	1139-12	7/23/2013	12	4878.4	17730	19.45	336	18.2	10900	1260	8.9
1139	1139-12.5	7/23/2013	12.5	4877.9	17777	19.11	334	18.2	10800	1170	8.8
1139	1139-13	7/23/2013	13	4877.4	17797	18.71	334	18.3	10800	1160	9.0
1139	1139-13.5	7/23/2013	13.5	4876.9	17864	18.12	333	18.4	10800	1100	9.0
1139	1139-14	7/23/2013	14	4876.4	19484	17.6	333	17.9	10600	1110	8.8
1139	1139-9	7/25/2013	9	4881.4	14052	27.17	328	17.8	10600	1090	8.8
1139	1139-9.5	7/25/2013	9.5	4880.9	14662	23.51	325	17.7	10500	1080	9.0
1139	1139-10	7/25/2013	10	4880.4	15093	22.08	329	17.9	10600	1140	8.9
1139	1139-10.5	7/25/2013	10.5	4879.9	15367	21.35	332	17.8	10600	1140	8.8
1139	1139-11	7/25/2013	11	4879.4	15548	20.73	335	18.1	10800	1050	8.7
1139	1139-11.5	7/25/2013	11.5	4878.9	15579	20.35	334	18	10800	1070	8.6
1139	1139-12	7/25/2013	12	4878.4	15603	19.99	332	18.1	10700	1140	8.5
1139	1139-12.5	7/25/2013	12.5	4877.9	15611	19.6	334	18	10700	1160	8.5
1139	1139-13	7/25/2013	13	4877.4	15614	19.16	331	17.6	10700	1060	8.7
1139	1139-13.5	7/25/2013	13.5	4876.9	15610	18.73	331	17.7	10700	1110	8.7
1139	1139-14	7/25/2013	14	4876.4	16222	18.03	NS	NS	NS	NS	NS