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Environmental Sciences Laboratory

Geology and Groundwater Investigation Many Devils Wash, Shiprock Site, New Mexico

April 2011

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Cover Photo: Seep Line and Efflorescence in Many Devils Wash

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Executive Summary

Investigations of groundwater and surface contamination at the Shiprock, New Mexico, Disposal and Processing Site, a former uranium-ore processing facility managed by the U.S. Department of Energy (DOE) Office of Legacy Management, have been ongoing for over two decades. A major focus of these investigations has been a prominent drainage, Many Devils Wash, located about 0.6 mile east of the disposal cell. The wash drains an area of about 11.5 square miles and enters the San Juan River just upstream of Shiprock. Elevated levels of nitrate, sulfate, selenium, and uranium detected in surface and seep water in the wash have raised concerns about potential human health or ecological risks, as well as increased contaminant loading to the river. These constituents are also contaminants of concern at the site, but contaminant transport mechanisms are not obvious. No mill tailings were ever placed in the vicinity of Many Devils Wash. To further investigate the source and nature of contamination in Many Devils Wash, DOE undertook this investigation in spring 2010. The occurrence of the efflorescence in Tributary 1 and observation of a nearly continuous trickle of seepage water at the confluence of East Fork with Many Devils Wash were instrumental in prompting this investigation.

A prevailing issue regarding the contamination at Many Devils Wash is determining source. The contamination may have reached Many Devils Wash by flowing from the mill site through the Mancos Shale that takes it under Many Devils Wash and then upward to the base of the loess on the east side of the wash. An alternate hypothesis is that the contamination is from naturally occurring processes similar to those in other areas that are underlain by Mancos Shale and that have high concentrations of nitrate, selenium, sulfate, and uranium in the groundwater. Fundamental to understanding the source of contamination is understanding the nature and extent of the contaminated groundwater system. This knowledge is also fundamental to designing a remediation system if it is needed. The purpose of this study was to better define the extent, chemistry, and surface of shallow groundwater in the Many Devils Wash area. The work included installation of 28 new sampling points, measurements of groundwater elevations, sampling and analysis of groundwater, elevation surveys of geologic contacts, and preliminary chemical analyses of loess samples.

The geology of the wash is dominated by Mancos Shale overlain by 20 to 30 feet (ft) of loess. Steeply incised channeling in the loess may be caused by groundwater sapping, a process that requires groundwater flow at the Mancos-loess contact. Observations made previously at Many Devils Wash indicated that much, if not all, of the contamination in the wash could come from an area south of East Fork, a tributary to Many Devils Wash. Perennial groundwater seepage has been observed at the confluence of East Fork with the main channel of Many Devils Wash. Field observations made in support of the current investigation were the first to detect groundwater in a side tributary to East Fork (Tributary 1), and it was found that groundwater extends at least 350 ft farther south than had previously been observed. The southernmost sampling point (EF-19) produced more groundwater than most other sampling points in our study, suggesting that groundwater saturation may extend even farther south. A bedrock paleochannel was defined that could exert control on groundwater flow from East Fork to the knickpoint seeps.

Groundwater samples were collected from all new sampling points. The concentrations of nitrate, selenium, sulfate, and uranium were reasonably similar among the samples as indicated by chemical contour plots. The chemistry was also similar to that measured in sampling points and seeps near the knickpoint of Many Devils Wash. The similarity of chemical signatures

indicates a common source. The concentrations of nitrate, selenium, sulfate, and uranium leached from the loess in laboratory tests were relatively low.

1.0 Introduction

Investigations of groundwater and surface contamination at the Shiprock, New Mexico, Disposal and Processing Site (Figure 1), a former uranium-ore processing facility managed by the U.S. Department of Energy (DOE) Office of Legacy Management (LM), have been ongoing for over two decades. A major focus of these investigations has been a prominent drainage, Many Devils Wash, located about 0.6 mile east of the disposal cell. The wash drains an area of about 11.5 square miles and enters the San Juan River just upstream of Shiprock (Figure 2). Elevated levels of nitrate, sulfate, selenium, and uranium detected in surface and seep water in the wash have raised concerns about potential human health or ecological risks, as well as increased contaminant loading to the river. These constituents are also contaminants of concern at the site, but contaminant transport mechanisms are not well understood. To further investigate the source of contamination in Many Devils Wash, DOE undertook this investigation in spring 2010.

For a half-mile length upstream of its confluence with the San Juan River, Many Devils Wash has incised through a loess-filled valley into Mancos Shale bedrock. A major tributary, East Fork, enters Many Devils Wash at the upper reach of this half-mile stretch. East Fork drains an area of 1.6 square miles (Figure 2) and is dry except during infrequent storm events. A dry tributary to East Fork, informally referred to as Tributary 1, extends south-southwest from its junction with East Fork and is also incised in loess deposits (Figure 3). This project focused on the half-mile terminus of Many Devils Wash, the portion of East Fork about 500 feet (ft) upstream from its confluence with Many Devils Wash, and Tributary 1 (shown in Figure 3 and Figure 4 as the South and North Project Areas, respectively). No mill tailings are known to have been placed in Many Devils Wash. A small ore-transfer station ("former Climax ore transfer station" on Figure 2) was used to stockpile uranium ores during the 1950s and 1960s (verbal communication with Bill Chenoweth); however, these ores were later removed and it is unlikely that they contributed to groundwater contamination in the project area.

Observations at Many Devils Wash indicated that much, if not all, of the contamination in the stream could have originated from the area of Tributary 1. Efflorescence (white salt deposits) can indicate locations of contaminated groundwater (Figure 5). Efflorescence in some areas is ephemeral and is washed away by rain events. However, some stretches of Many Devils Wash contain persistent efflorescence. An oblique aerial photo available on the Microsoft Bing website captured the white efflorescence at a time when it appeared to originate in Tributary 1, extend down a short stretch of East Fork, and then down Many Devils Wash to its confluence with the San Juan River (Figure 6). Efflorescence is not present in the main channel of Many Devils Wash where it parallels Tributary 1 to the west and is absent in East Fork upstream of the confluence with Tributary 1. The occurrence of the efflorescence in Tributary 1 and observation of a nearly continuous trickle of seepage water at the confluence of East Fork with Many Devils Wash were instrumental in prompting this investigation. The purpose of the study was to better define the nature and extent of groundwater saturation and the contamination profile in East Fork and Tributary 1. It was hypothesized that all of the surface water in the stream channel and groundwater issuing from seeps in Many Devils Wash may originate from the Tributary 1 area. If the hypothesis is correct, the contamination in Many Devils Wash could be remediated by capturing it at Tributary 1. Main components of the study include detailed geologic mapping, bedrock surface contouring, installation of 28 hand-bored sampling points, water table mapping, and analysis of groundwater and sediment chemistry.

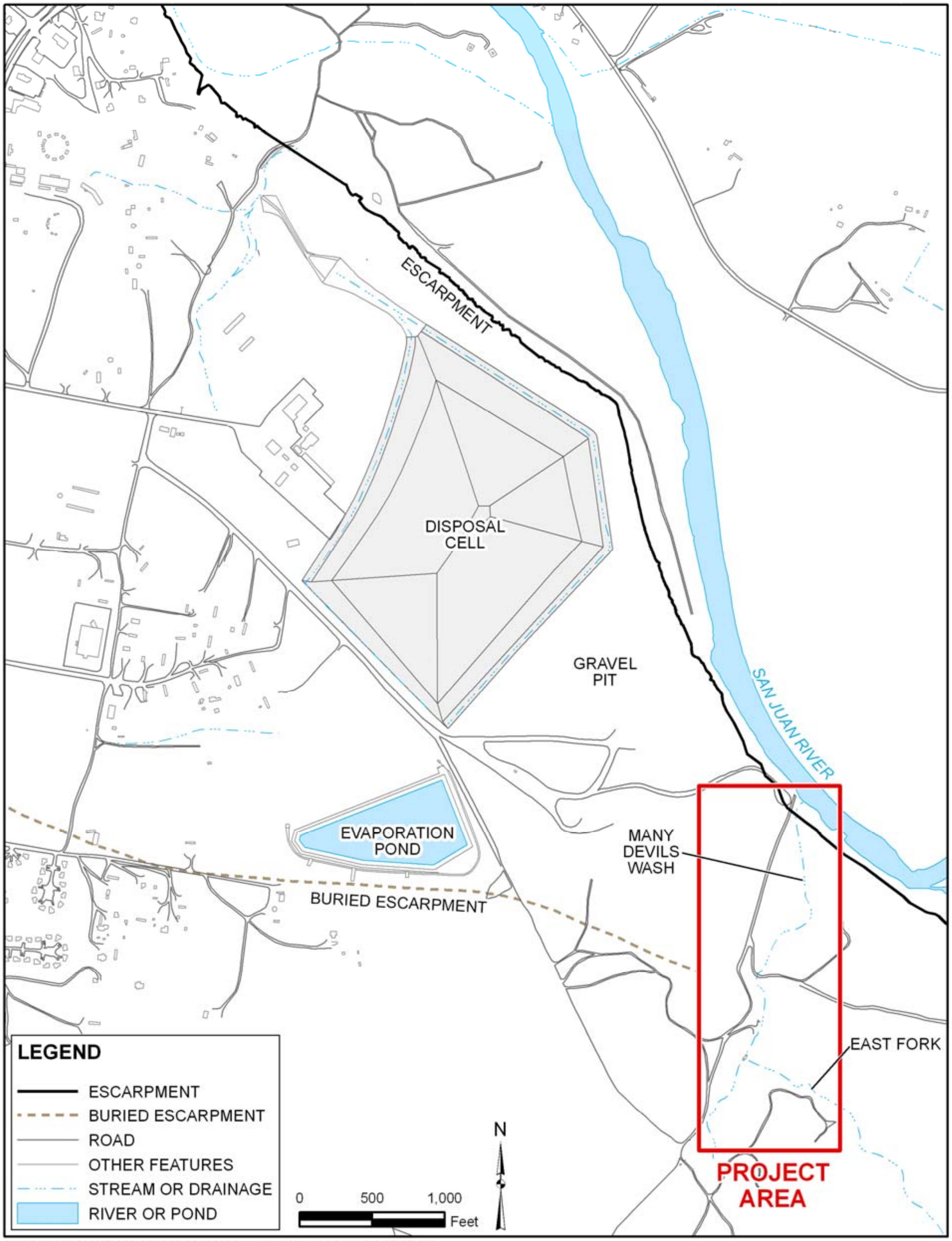

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Figure 1. Location Map

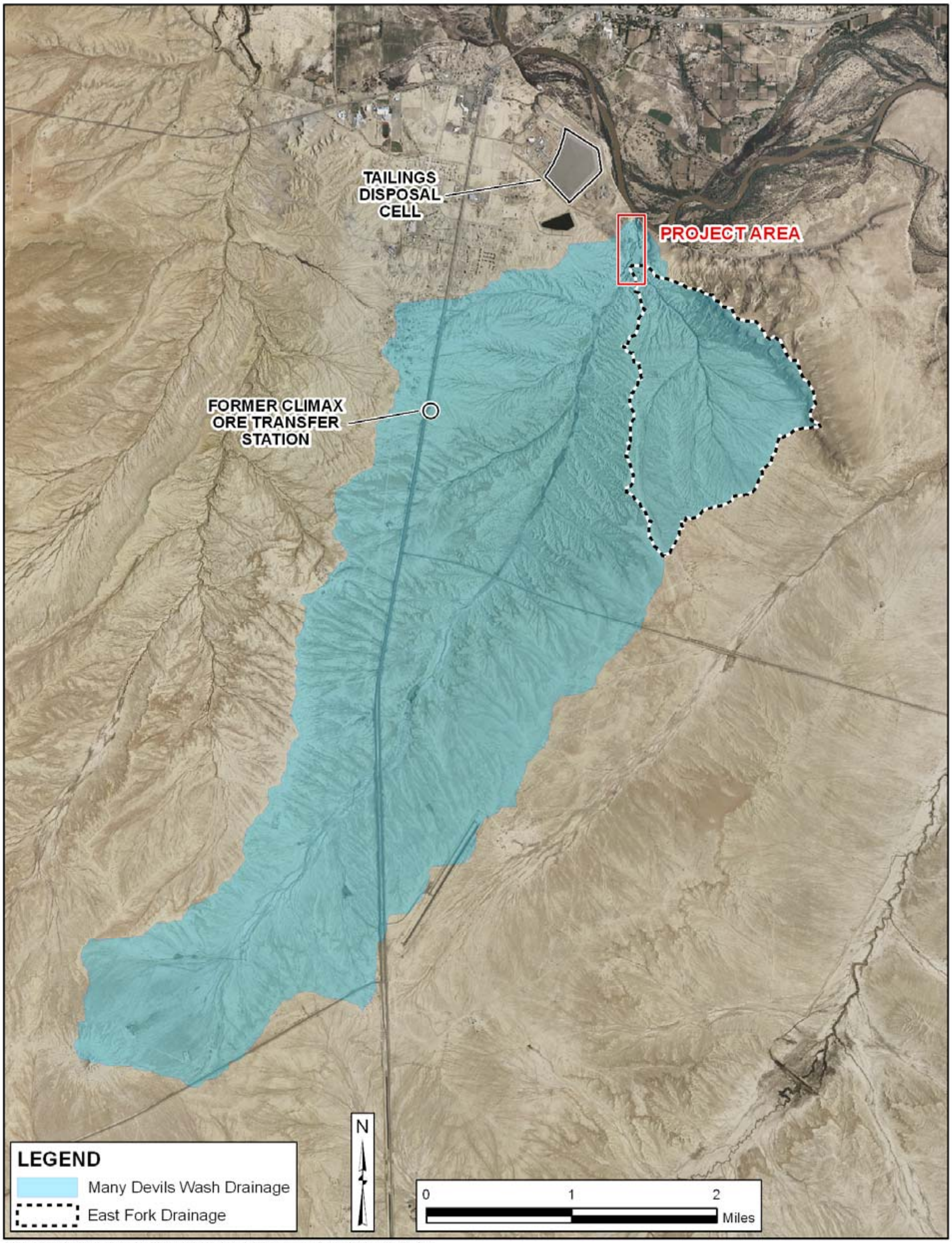

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Figure 2. Many Devils Wash (Blue) and East Fork (Dashed Line) Drainage Basins

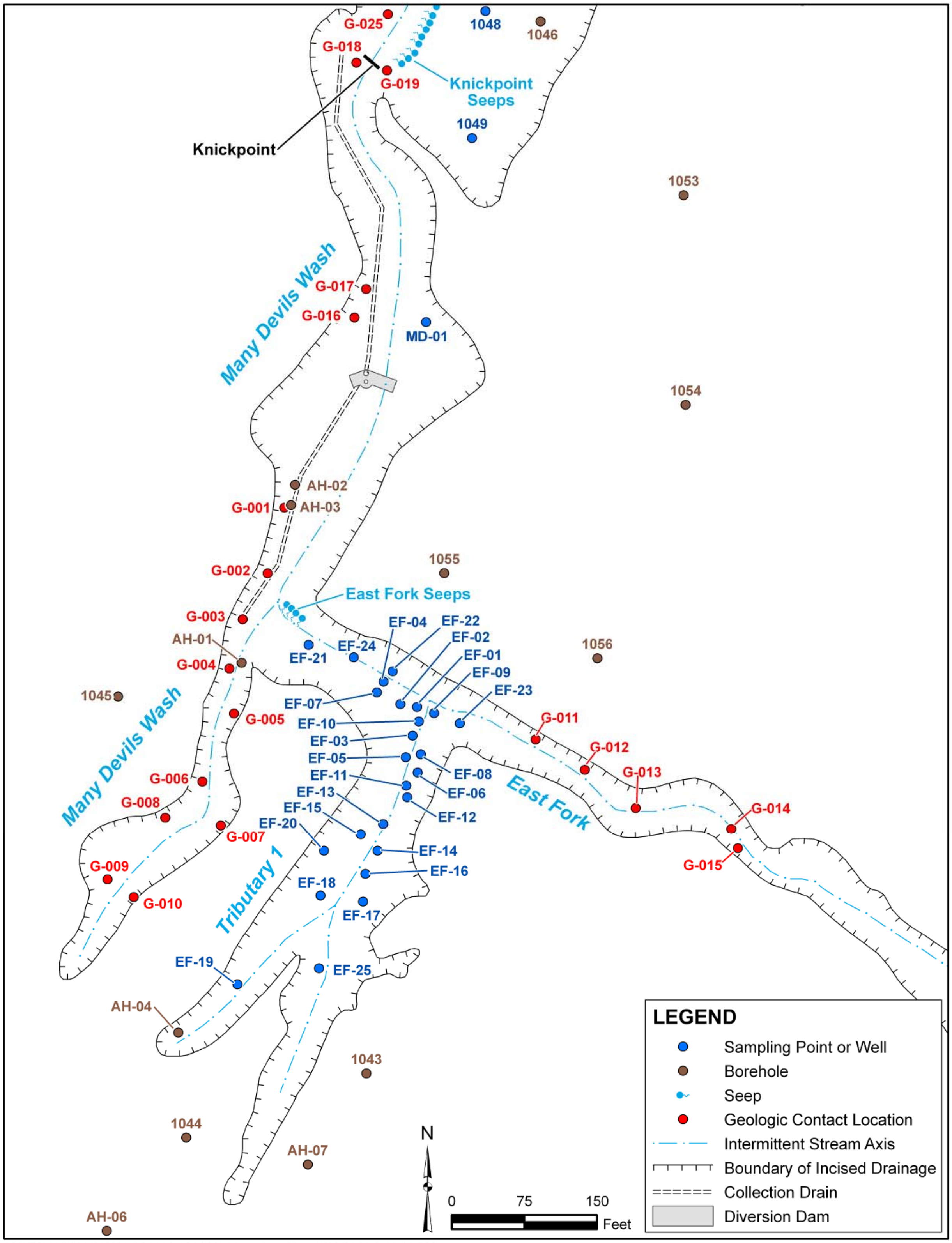

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Figure 3. Location Map of South Project Area

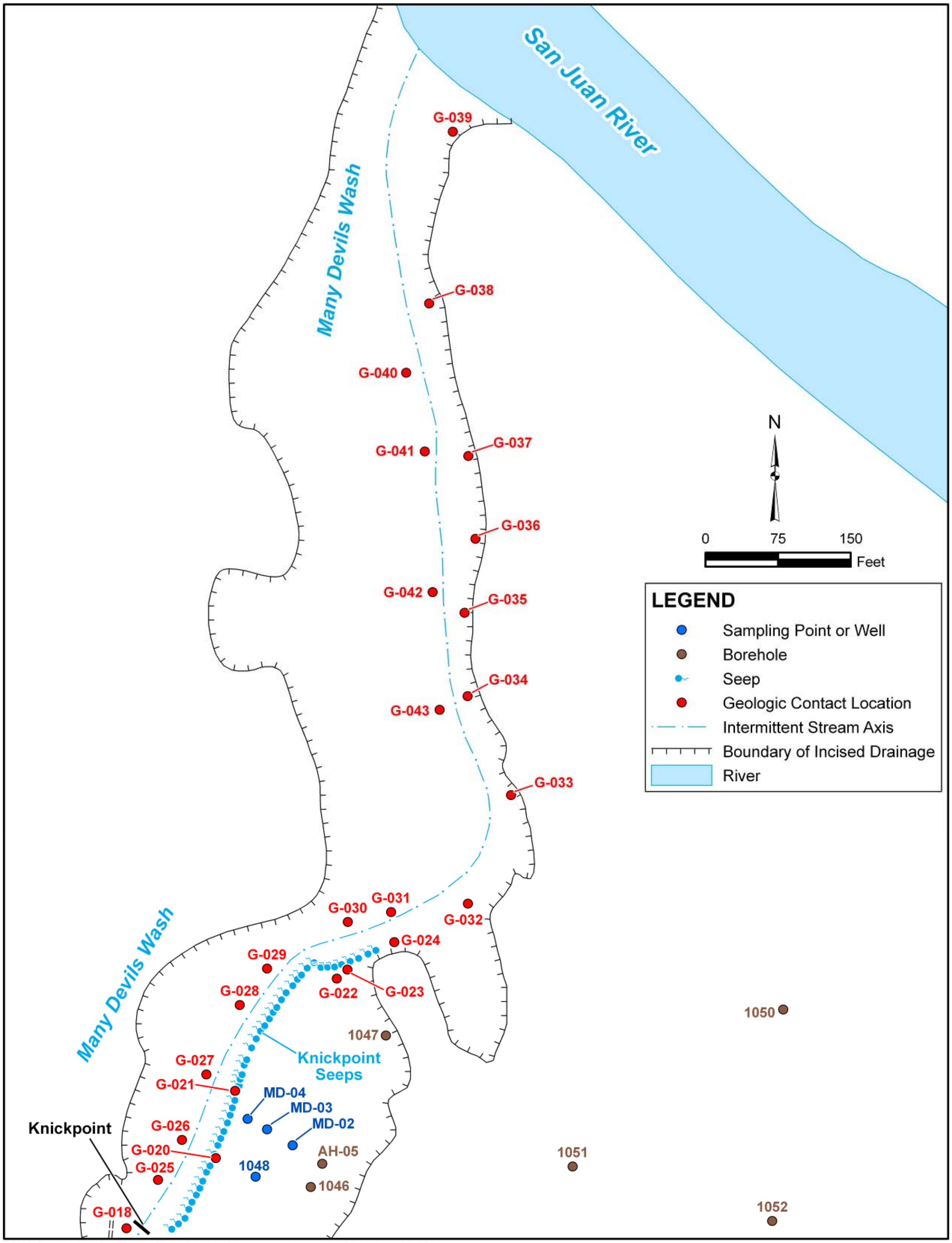

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Figure 4. Location Map of North Project Area

Figure 5. Efflorescence in East Fork
(Looking west, sampling point EF-10 in foreground)

Figure 6. Oblique Air Photo of Project Area Showing Efflorescence Extending from Tributary 1 to the Mouth of Many Devils Wash
(Farthest upstream efflorescence is at the tip of the Tributary 1 arrow. Photo base is from the Microsoft Bing website.)

Pools of yellow- to red-colored water are common in the stream channel of Many Devils Wash (Figure 7). The color of the water depends on its depth. Where the water is less than several inches deep, it is light yellow, but where the depth is more than about 1 ft, the color is deep red. The source of the yellow and red colors has not been determined. The pools contain high concentrations of nitrate, selenium, sulfate, and uranium, which are constituents found as groundwater contaminants near the former mill site. These same constituents are detected in groundwater that feeds a line of seeps along the eastern side of Many Devils Wash below the knickpoint seeps. Because these constituents are found at the former mill site, DOE considers Many Devils Wash to have been contaminated by the milling operation and is accordingly engaged in remediation of the wash (DOE 2000, 2002, 2004).

However, there are uncertainties with an interpretation of mill site contamination. For example, contaminated groundwater migrating from the mill site is expected to daylight on the west side of Many Devils Wash, but instead it seeps from the east side of the wash. Outcrops of the same strata occur at the same elevation on the west side which would be the first point at which groundwater flowing through these beds from the mill site would intersect the wash. Thus, if the seepage is from the mill site it must follow an atypical flow path to appear on the east side. This paradox and other factors led some investigators to consider the hypothesis that all or part of the contamination at Many Devils Wash may come from an alternate source or may be a natural occurrence.

Figure 7. Standing Pools of Red-Colored Water are Typical of Many Devils Wash.
Cobbles (arrows) placed to cover the standing pools of water have mostly been washed downstream.
Photo is taken about 400 ft downstream of the knickpoint seeps, looking north.

2.0 Site History

The Shiprock site was used for milling of uranium and vanadium ores from 1954 through 1968 and processed about 1.5 million tons of ore (DOE 2000). Unlined tailings ponds and raffinate ponds were used at the site during operation of the mill (Figure 8). Surface remediation of the mill site in 1985 and 1986 included decommissioning of mill site buildings and facilities and stabilizing tailings and associated materials into the on-site disposal cell, shown in Figure 1.

Figure 8. 1965 Aerial Photo of Mill Site Looking East and Showing Locations of Raffinate Ponds and Many Devils Wash

In 1999, DOE drilled 18 boreholes in and near the Many Devils Wash project area to search for groundwater and determine the thickness of the loess deposits. Only two of these boreholes encountered saturated groundwater conditions. The two that intercepted groundwater (1048 and 1049) are located near the line of knickpoint seeps on the east side of Many Devils Wash and were made into wells (Figure 3). In July 2009, well 1049 was equipped with a transducer and connected to LM's System Operation and Analysis at Remote Sites (SOARS) system for real-time monitoring of groundwater levels.

To limit access to the surface water in Many Devils Wash, two interim actions were conducted in the summer and fall of 2000. The wash was fenced to prevent access by cattle, and a cobble blanket was used to cover contaminated pools. In July 2001, flooding caused major removal of the cobble blanket, rendering it relatively ineffective for access control (Figure 7). In

November 2002, a 400-ft-long collection drain was installed in Many Devils Wash to capture surface water and shallow groundwater (Figure 3); it began operating in March 2003. Captured contaminated water is removed from the wash by pumping to an 11-acre evaporation pond. Instruments to measure flow rates and water levels in the collection sump were installed in December 2005 and connected to SOARS for real-time monitoring. The efficiency of the collection drain decreased over time in part because accumulation of fine-grained sediment is limiting the infiltration of surface water into the drain. To help capture the contaminated surface water, a diversion dam was built in August 2009 (Figure 3). The wash has since dried up for about 300 ft downstream of the diversion dam. However, perennial pools of water exist upstream of the diversion structure and downstream of the knickpoint seeps. The knickpoint is an erosion resistant outcrop of bedrock that forms a small waterfall when the wash is running.

3.0 Compliance Strategy

Remediation requirements are defined in the Groundwater Compliance Action Plan (GCAP) (DOE 2002). Because the Shiprock site has major physiologic and hydrologic differences, the GCAP divides the site into terrace and floodplain regions, each with its own compliance strategy. The compliance strategy for the terrace is active remediation until potential risks are eliminated. For Many Devils Wash, contaminated water is pumped from the collection drain to the evaporation pond. Potential exposure paths in Many Devils Wash are presumed to be eliminated when the seeps no longer flow. The GCAP does not offer a prediction for how long the remediation would take in Many Devils Wash; however, it predicts that 7 years is required for remediation of the other portions of the terrace. This prediction has not been met, in part because of less-than-anticipated removal rates of groundwater from extraction wells. Remediation should have been complete by 2009.

Most of the data from the Shiprock site collected prior to 2000 are discussed in the Site Observational Work Plan (SOWP), a comprehensive report that documents the technical aspects of the site leading up to the selection of an overall compliance strategy (DOE 2000). In the SOWP, contamination in Many Devils Wash is considered to have come from the mill site. High nitrate and uranium concentrations in samples from Many Devils Wash are cited as evidence for mill site contamination (SOWP, p. 4–78 and p. 4–123). Although not explicitly stated, the SOWP (p. 4–124) infers that high concentrations of selenium and sulfate also indicate a mill site source. The SOWP also states that the chemistry of the surface water in Many Devils Wash is significantly different from that of groundwater in wells along potential flow paths from the mill site. The chemical differences are explained by interaction with Mancos Shale, although no definitive chemical transfer mechanisms are provided. In contrast to the view that the contamination in Many Devils Wash is site related, the SOWP (p. 4–213) also states that the uranium in Many Devils Wash may be naturally occurring and suggests that application of supplemental standards may be appropriate. This argument is based on higher values of uranium-234 to uranium-238 activity ratios in Many Devils Wash than in the mill site area.

The postulated pathway for mill fluids to reach Many Devils Wash from the mill site is only partially explained in the SOWP. Apparently, fluids were thought to have moved down vertically from unlined mill ponds through the underlying weathered Mancos Shale and encountered an impermeable siltstone bed that dips gently eastward and intercepts a portion of the wash above its bed. The fluid migrated on top of the siltstone bed to the vicinity of Many Devils Wash.

Because seepage into Many Devils Wash occurs only along the east side of the wash and none occurs on the west side (closest to disposal cell), the fluid moving eastward must infiltrate through the siltstone bed and a portion of the underlying Mancos Shale before reappearing on the east side of the wash, possibly following a north-northeast striking joint system. The SOWP does not explicitly explain the pathway by which contamination has moved from the mill site to Many Devils Wash; however, the general concept involving the siltstone bed in the Mancos Shale was provided to the authors via discussions with investigators that contributed to the SOWP. The complex nature of fluid pathways in Many Devils Wash has puzzled investigators for years.

4.0 Geology

Bedrock underlying the Many Devils Wash area is the Late Cretaceous Mancos Shale that dips gently eastward. Overlying the Mancos Shale are unconsolidated Quaternary deposits of terrace material deposited by the ancestral San Juan River, loess, and alluvium/colluvium. Many Devils Wash is north-draining and approximately 6 miles long; the final 2,500 ft of its course to the confluence of the San Juan River has a narrow channel cut into the Mancos Shale. South of this, the Many Devils Wash bottom is much wider and is on loess. At the south edge of the site area, incision of the wash is advancing southward by erosional headcutting into loess. The incision of Many Devils Wash and its tributaries into loess for its final (approximately 0.5 mile) course to the San Juan River has created a pseudokarst topography resulting from piping erosion (Parker and Higgins 1990).

Some of the following geologic discussion is taken from characterization work described in the SOWP (DOE 2000). Geologic mapping at a small scale provided for the SOWP was revised and developed in more detail at a larger scale (1:1,200) to encompass the Many Devils Wash site area (Figure 9 and Figure 10). Two geologic cross sections across Many Devils Wash were prepared to show the geologic relationships of Mancos Shale to the Quaternary deposits in the north part of the project area around the knickpoint seeps and in the south part around Tributary 1 (Figure 11). Elevations of the top of bedrock (Mancos Shale) surface for the project area were determined using geologic contact points established and surveyed at numerous locations where Mancos Shale is overlain by either loess or alluvium/colluvium. Elevations of the top of bedrock found in boreholes and wells were also used to prepare the top of the bedrock surface.

4.1 Mancos Shale

Steel-gray marine mudstone of the Mancos Shale, deposited in the Western Interior Seaway, crops out in Many Devils Wash and in the low hills east and west of the wash. The shale in the Many Devils Wash area is near the middle of the thick Mancos Shale section—approximately 1,000 ft of the Mancos underlies the area. Best exposures are where Many Devils Wash has incised its narrow channel as much as 20 ft into hard, well-bedded shale that is unweathered in places. In most other areas in the surrounding hills, Mancos Shale exposures are weathered, bedding is poorly exposed, and the soft, gray-tan material resembles colluvium. The weathered zone may extend to depths of as much as 40 ft. In this zone, fractures typically contain authigenic gypsum, which formed by oxidation of disseminated pyrite, creating sulfuric acid that reacts with calcite to form gypsum (White and Greenman 2008). Expansion causes fracturing and heaving in the weathered shale when calcite recrystallizes to gypsum.

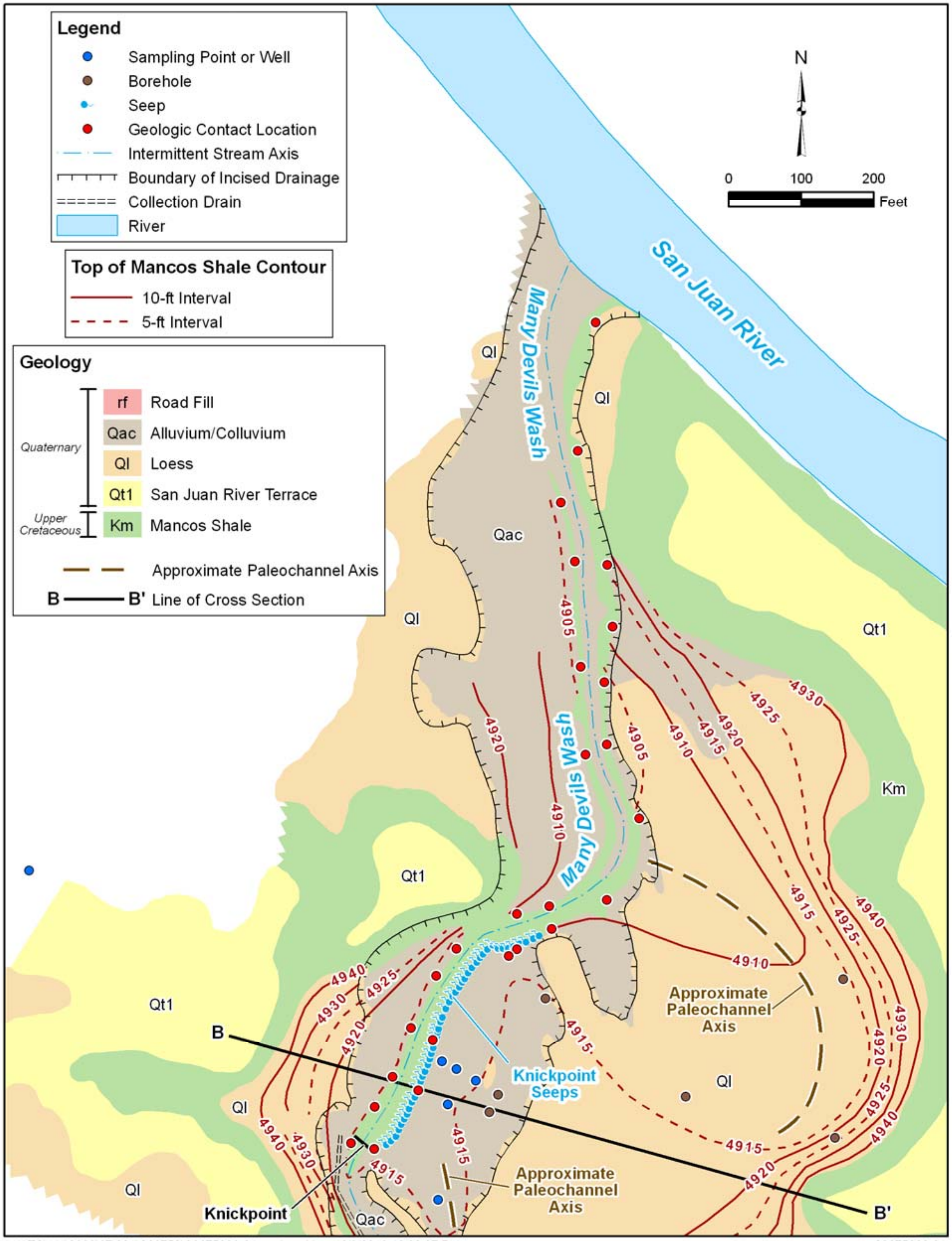

Figure 9. Geologic Map of the North Project Area, with Cross Section Line and Elevation Contours of the Mancos Shale Bedrock Surface (see Figure 4 for Location Identifiers)

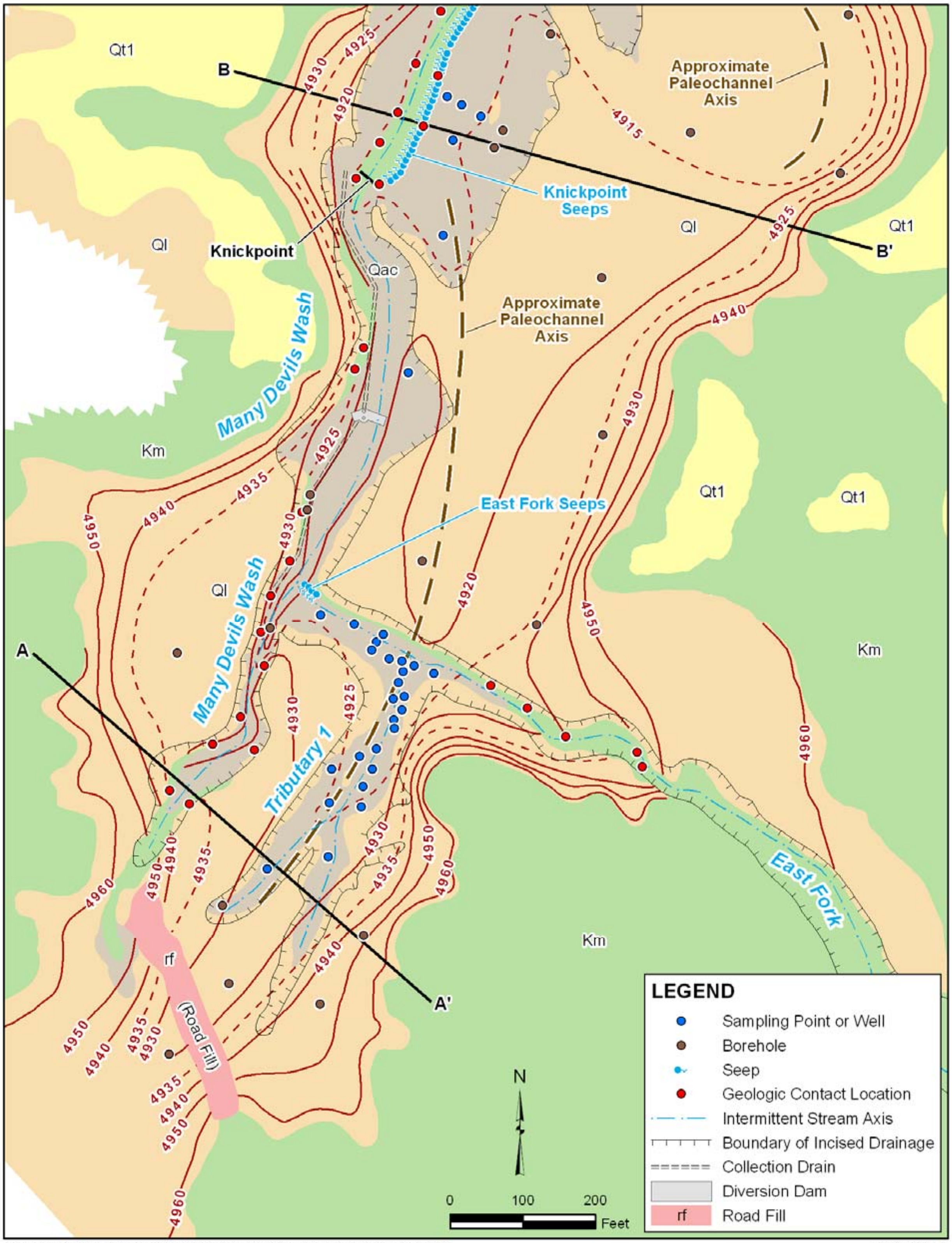

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Figure 10. Geologic Map of the South Project Area, with Lines of Cross Sections and Elevation Contours of the Mancos Shale Bedrock Surface (see Figure 9 for Geology Legend and Figure 3 for Location Identifiers)

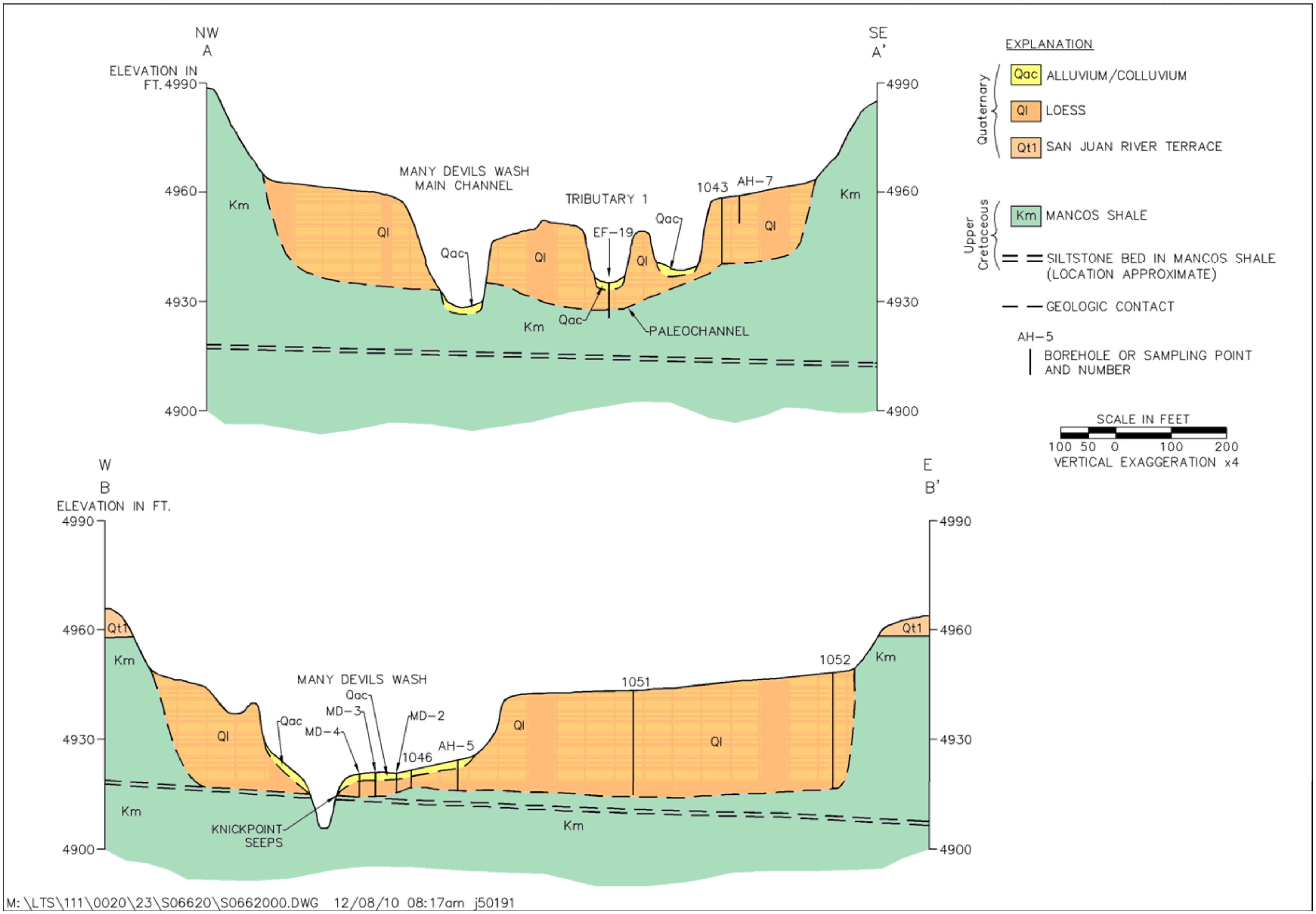

Figure 11. Cross Sections A-A' and B-B'
(see Figure 10 for location of cross sections)

A continuous, distinctive, resistant, fossiliferous, marker bed of calcareous siltstone about 1 ft thick crops out and forms a knickpoint in Many Devils Wash about 1,200 ft upstream from the confluence with the San Juan River. The siltstone marker bed weathers to a tan-to-orange color and can be followed in semicontinuous outcrops downstream from the knickpoint along the walls of the incised wash. The outcrop of the siltstone bed can be followed along the escarpment downstream from the confluence of Many Devils Wash and the San Juan River to the area of seep 0427 north of the disposal cell. Surveyed elevations of the top of the siltstone bed indicate that the strike of Mancos Shale is approximately north, and the dip of the shale in the Many Devils Wash area is about 0.5 degree to the east (DOE 2000). Joints measured in the disposal cell escarpment area are vertical, and the principal joint set strikes northeast to north-northeast (DOE 2000), which is approximately parallel to Many Devils Wash.

4.2 Terrace Deposits of the Ancestral San Juan River

Terrace deposits about 10 to 20 ft thick cap some Mancos Shale slopes east and west of Many Devils Wash downstream (north) of the confluence of the East Fork. These deposits, mapped as Qt1, consist of clast-supported, well-rounded gravel, cobbles, and boulders with a silty and sandy matrix. The base of the terrace deposits is 50 to 60 ft above the present San Juan River floodplain, and the deposits represent glacial outwash during aggradation in the former San Juan River valley during the late part of the Bull Lake glaciation about 100,000 to 120,000 years ago. Most of the resistant cobbles and boulders consist of metamorphic rocks transported from their source in the San Juan Mountains.

Later erosion and downcutting by Many Devils Wash have removed most of these terrace deposits, and scattered remnants now cap strath terraces. An example of these remnant terrace deposits is the gravel capping the small hill about 350 ft north of the knickpoint in Many Devils Wash (Figure 9). Erosion of the gravel terraces contributes gravel and cobbles to Many Devils Wash, mainly north of the knickpoint. Gravel and cobbles eroded from an older San Juan River terrace deposit capping a higher elevation strath surface about 1 mile to the southeast have been transported down the East Fork drainage. No terrace deposits are present in the Many Devils Wash drainage south of the East Fork confluence.

4.3 Loess

Loess, mapped as Ql on Figure 9 and Figure 10, as thick as 30 ft has filled an earlier valley (or paleovalley) of Many Devils Wash. The more recent Many Devils Wash drainage has incised into and removed much of the loess. The loess, deposited on the Mancos Shale, is a distinctive yellow-tan color and consists mainly of silt, clay, and very fine grained sand. Most of the loess is fine-grained, indicating an eolian origin; however, the lowermost 2 to 3 ft of loess is typically mixed with some sand and small pebbles, indicating fluvial deposition. Much of the loess was derived from ablation of extensive Mancos Shale areas to the south and west where the winds picked up smectitic clay with swelling characteristics. The loess was probably deposited in mid-Holocene time during a dry period approximately 2,800 to 6,000 years ago (Love and Gillam 1991).

Where not eroded by the Many Devils Wash system, the top of the loess typically forms a flat surface, as is preserved in the area east of the wash and north of East Fork. Erosional headcutting by Many Devils Wash and its main tributary, East Fork, have incised the loess and have created through piping erosion (Parker 1963) a pseudokarst topography of cliffs, pillars, and towers (Parker and Higgins 1990). The process of precipitation, infiltration, groundwater flow in the lower, more coarse-grained part of the loess, and sapping are shown in the schematic diagram (Figure 12) of a typical loess exposure along Many Devils Wash. Sapping, caused by the piping of groundwater through the more coarse fluvial material in the lowermost part of the loess may be partially responsible for the headward incision and collapse of pillars in Many Devils Wash and its tributaries.

Approximately 250 ft south of the head of incision in Many Devils Wash (immediately southwest of the rf unit on Figure 10), where the loess-filled valley is wide and flat, is a several-acre area that contains small, roughly circular mounds 1 to 2 ft high and about 2 ft across (Figure 13). The mounds often have vegetation growing on them indicating that they form by differential erosion around the vegetation. Preliminary field reconnaissance suggests that occurrences of this feature coincide with headward erosion of deeply incised channels in the loess formed by the sapping process.

4.4 Alluvium/Colluvium

Soft, alluvial and/or colluvial material less than 3 ft thick, mapped as Qac, covers some areas of loess and Mancos Shale. Some of this material is formed by collapse and erosion of the loess towers and cliffs and covers low slopes mainly in areas east and west of the wash below the knickpoint and wash bottoms such as the East Fork and Tributary 1. Other areas where Qac is mapped may be mostly alluvial in origin, such as along the bottom of Many Devils Wash.

4.5 Mancos Shale Bedrock Surface

The two cross sections (Figure 11) and the bedrock surface contour map (Figure 9 and Figure 10) show the topography of the Many Devils Wash valley before the loess was deposited. Bedrock contours from numerous boreholes in Tributary 1 show a paleochannel of Many Devils Wash approximately 150 to 200 ft east of and subparallel to the present wash (Figure 10). This paleochannel continues northward just east of borehole 1055, extends to the area of wells 1048 and 1049, and joins the present wash in the area of the knickpoint seeps. Another probable paleochannel is to the north-northeast from the area of borehole 1053 where the ancestral wash carved an arcuate channel against Mancos Shale cliffs to the east before entering the present channel of the wash about 500 ft south of its confluence with the San Juan River (Figure 9). Additional boreholes drilled to bedrock north of boreholes 1050 and 1052 would be necessary to confirm the presence of this other paleochannel.

Cross section A-A′ shows the location of the Many Devils Wash paleochannel at sampling point EF-19 in Tributary 1 (Figure 11). A relatively high production rate of groundwater has been measured at EF-19 and several other sampling points in Tributary 1 near the paleochannel axis, indicating that groundwater may fill the northward-trending paleochannel. Moist, but not saturated, conditions were indicated for a several-foot thickness in the lower, coarse-grained part of the loess at borehole 1055. Groundwater at well 1049 and the presence of the knickpoint seeps along the east side of the present wash also support the interpretation of northward flow of groundwater along this paleochannel. Cross section B-B′ shows the distal end of this paleochannel where the top of bedrock is at the top of the siltstone bed, and groundwater occurs

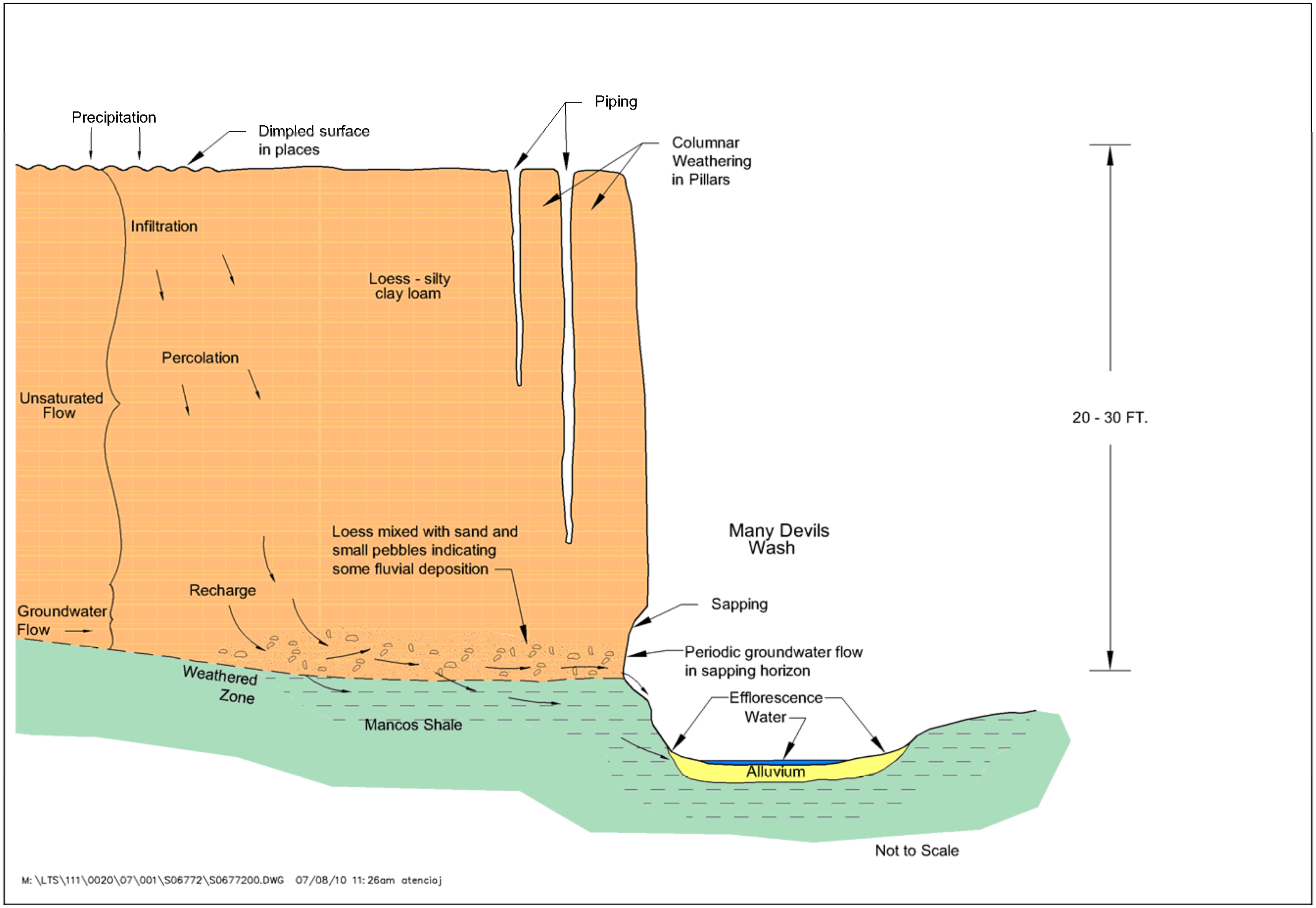

Figure 12. Schematic Diagram of Loess and Groundwater Sapping Along Many Devils Wash

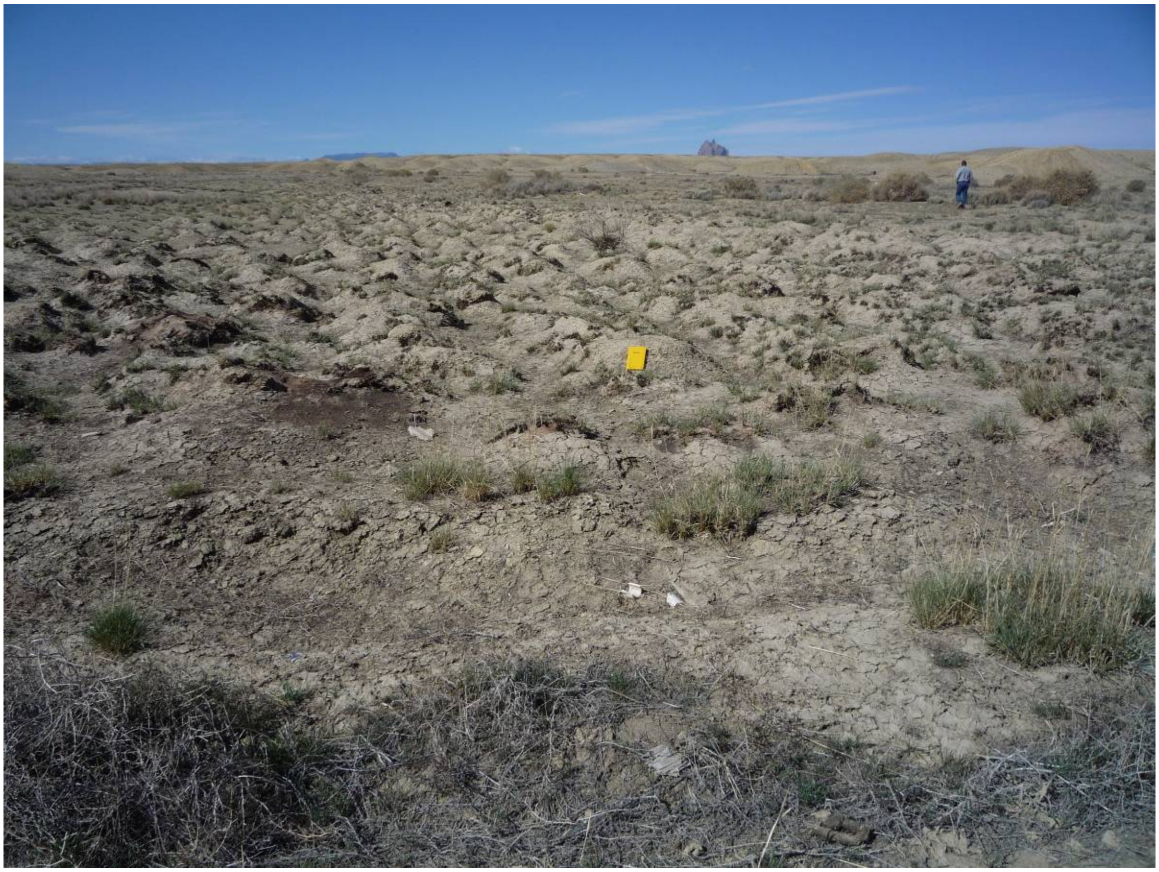

Figure 13. Mounded Surface about 250 ft South of the Head of Incision of Many Devils Wash

there in the new sampling points MD-2 through MD-4, but groundwater was absent in boring AH-5. South of Tributary 1 and south of the old road (with cemented cobble-rock retaining walls, circa 1930s, to the Hogback oil field, see unit rf on Figure 10), additional depth-to-bedrock data are needed to determine the position of the paleochannel and whether groundwater is present.

4.6 Efflorescence

Groundwater seepage and ponded water is indicated by efflorescence in many places along Many Devils Wash. This white powdery precipitate may be as much as 0.25 inch thick and is particularly common where Mancos Shale is saturated as in the area of the knickpoint seeps. Efflorescence is also common on the alluvium/colluvium overlying saturated Mancos Shale where water is ponded in Many Devils Wash above the diversion dam. Efflorescence extends from this area up the East Fork and south up Tributary 1 and indicates the presence of shallow groundwater.

5.0 Methods

Sampling points, mapped in Figure 3 and Figure 4, were installed with a hand-held coring tool (Figure 14). At the desired depth, the coring tool was removed, and a 2-inch-diameter PVC pipe with 1 ft of slotted casing near the bottom and a cap was pushed into the hole. In most cases, the hole remained open and the pipe could be pushed to the full depth that was cored. Hand coring is limited to depths of about 10 to 15 ft in these soils. Sand was poured into the annulus and the upper 1 ft was packed with native soil. U.S. Silica Company natural silica 20- to 40-mesh well sand was used in most completions; however, Home Depot–grade "play sand" was used as a substitute when well sand was not available. There did not appear to be a correlation between production rate and the type of sand used.

Figure 14. Sample Point Being Installed in Tributary 1 Using Hand Coring Device

Table 1 provides completion and elevation data for the sampling points. Elevations were measured with a survey-grade level and stadia rod using top of casing at well 1049 as a reference. Spatial coordinates were determined with a Trimble model GeoXT 2005 Global Positioning System (GPS) (Table 2).

Table 1. Completion Data for Hand-Bored Sampling Points (EF and MD) and Borings (AH) (all casings are 2-inch diameter)

Sampling Point ID	Date Drilled	TOC Elev (ft)	TD (ft BGS)	Stick-Up (ft)	Screen Top (ft BTOC)	Slot Size (inches)	Sand Pack
EF-01	3/9/2010	4,926.28	2.6	1.46	3	0.02	Play Sand
EF-02	3/9/2010	4,926.28	2.33	1.71	3	0.02	Play Sand
EF-03	3/9/2010	4,926.84	3.52	0.42	3	0.02	Play Sand
EF-04	3/9/2010	4,925.26	3.18	0.8	3	0.02	Play Sand
EF-05	3/9/2010	4,928.3	4.3	0.73	4	0.02	Play Sand
EF-06	3/9/2010	4,928.29	6.4	0.35	6.25	drilled 0.132	Play Sand
EF-07	3/9/2010	4,924.64	2.08	0.52	1.5	drilled 0.132	Play Sand
EF-08	3/9/2010	4,927.58	5.42	0.18	5.1	drilled 0.132	Play Sand
EF-09	3/11/2010	4,926.51	4.18	0.96	4.13	0.02	Play Sand
EF-10	3/11/2010	4,926.14	1.93	1.12	2	0.02	Play Sand
EF-11	3/11/2010	4,928.08	6.75	0.3	6	0.02	Play Sand
EF-12	3/17/2010	4,930.34	7.06	1.76	8	0.02	Play Sand
EF-13	3/17/2010	4,931.22	7.2	2.1	8.3	0.02	Well Sand
EF-14	3/17/2010	4,930.4	7.66	1.11	8	0.02	Well Sand
EF-15	3/17/2010	4,930.12	6.13	1.16	6.15	0.02	Well Sand
EF-16	3/17/2010	4,931.06	6.45	1.05	6.5	0.02	Well Sand
EF-17	3/17/2010	4,932.32	6.25	1.28	6.5	0.02	Well Sand
EF-18	3/17/2010	4,932.84	7.61	0.9	7.7	0.02	Well Sand
EF-19	3/17/2010	4,935.47	7.67	2.78	8	0.02	Well Sand
EF-20	3/17/2010	4,931.53	5.91	0.92	6	0.02	Well Sand
EF-21	3/18/2010	4,925.16	1.56	2.07	2.6	0.02	Well Sand
EF-22	3/18/2010	4,926.69	3.78	0.72	3.5	0.02	Well Sand
EF-23	3/18/2010	4,926.01	3.62	1.38	4	0.02	Well Sand
EF-24	3/18/2010	4,924.52	1.89	0.61	1.5	0.02	Well Sand
EF-25	4/20/2010	4,919.49	6.36	1.14	6.5	0.02	Well Sand
MD-01	4/19/2010	4,929.46	4.93	1.72	6	0.02	Well Sand
MD-02	4/20/2010	4,922.53	6.86	1.14	7	0.02	Well Sand
MD-03	4/20/2010	4,921.99	6.6	1.2	6.8	0.02	Well Sand
MD-04	4/20/2010	4,924.36	8.43	1.67	9.1	0.02	Well Sand
AH-01	4/19/2010	4,922.52	3.8	na	na	na	na
AH-02	4/19/2010	4,923.05	2.1	na	na	na	na
AH-03	4/19/2010	4,921.96	2.0	na	na	na	na
AH-04	4/20/2010	4,935.3	5.2	na	na	na	na
AH-05	4/21/2010	4,921.985	6.0	na	na	na	na
AH-06	4/21/2010	4,941.83	6.8	na	na	na	na
AH-07	4/23/2010	4,957.45	7.0	na	na	na	na

na = not applicable; TOC = top of casing; BTOC = below top of casing

Table 2. GPS Survey Data for Hand-Bored Sampling Points (EF and MD) and Borings (AH)

Sampling Point ID	State Plane East	State Plane North	UTM East	UTM North	Longitude	Latitude
EF-01	252664.502	2096763.071	707249.4953	4070696.745	–108.678205	36.759405
EF-02	252647.213	2096765.952	707244.2091	4070697.394	–108.678264	36.759412
EF-03	252659.768	2096733.470	707248.3769	4070687.615	–108.67822	36.759323
EF-04	252629.821	2096789.237	707238.6802	4070704.365	–108.678324	36.759476
EF-05	252652.832	2096711.242	707246.4878	4070680.797	–108.678243	36.75926201
EF-06	252665.002	2096695.324	707250.3531	4070676.116	–108.678201	36.759219
EF-07	252622.836	2096778.092	707236.621	4070700.874	–108.678348	36.759445
EF-08	252668.335	2096714.214	707251.1952	4070681.91	–108.67819	36.759271
EF-09	252681.951	2096756.702	707254.8976	4070694.989	–108.678145	36.759388
EF-10	252666.303	2096748.162	707250.2306	4070692.211	–108.678198	36.759364
EF-11	252653.250	2096681.871	707246.8844	4070671.814	–108.678241	36.75918101
EF-12	252654.319	2096669.745	707247.3303	4070668.161	–108.678237	36.759148
EF-13	252629.300	2096641.989	707240.0384	4070659.435	–108.678321	36.759071
EF-14	252623.673	2096614.367	707238.5467	4070650.961	–108.67834	36.758995
EF-15	252606.319	2096631.382	707233.1528	4070656.049	–108.678399	36.75904201
EF-16	252611.073	2096590.343	707234.9747	4070643.547	–108.678382	36.758929
EF-17	252608.674	2096561.649	707234.5625	4070634.767	–108.678389	36.75885
EF-18	252564.760	2096568.013	707221.1278	4070636.217	–108.678539	36.758866
EF-19	252478.967	2096476.092	707195.8318	4070607.405	–108.67883	36.75861201
EF-20	252568.350	2096614.228	707221.6787	4070650.33	–108.678529	36.758993
EF-21	252552.414	2096827.188	707214.7474	4070715.109	–108.678589	36.759578
EF-22	252639.193	2096799.894	707241.459	4070707.652	–108.678292	36.759505
EF-23	252708.627	2096746.147	707263.0999	4070691.969	–108.678054	36.75935901
EF-24	252599.020	2096814.212	707229.0338	4070711.681	–108.67843	36.759544
EF-25	252563.215	2096492.851	707221.4145	4070613.354	–108.678542	36.75866
MD-01	252673.812	2097160.305	707248.3435	4070817.84	–108.678185	36.760496
MD-02	252773.241	2097513.904	707275.095	4070926.512	–108.677856	36.761469
MD-03	252746.899	2097530.337	707266.8499	4070931.308	–108.677947	36.761514
MD-04	252726.86	2097541.062	707260.7011	4070934.378	–108.678015	36.761543
AH-01	252483.248	2096808.683	707193.8181	4070708.828	–108.678825	36.759526
AH-02	252538.388	2096992.478	707208.7937	4070765.367	–108.678642	36.760032
AH-03	252534.218	2096971.41	707207.6999	4070758.902	–108.678656	36.759974
AH-04	252417.804	2096426.407	707177.7227	4070591.644	–108.679037	36.758474
AH-05	252803.973	2097494.78	707284.6061	4070921.081	–108.677751	36.761418
AH-06	252343.968	2096221.554	707157.2781	4070528.533	–108.679283	36.75791
AH-07	252551.695	2096290.188	707219.8784	4070551.479	–108.678576	36.758103

UTM = Universal Transverse Mercator

Sampling points were developed within a day of completion by pumping and, in a few cases, using a surge block. Some sampling points went dry with minimal pumping, but groundwater levels recovered when left overnight. In most cases the pumped groundwater was reasonably sediment free after one to three pump cycles. All pumped water had a yellow color similar to the knickpoint seep water. Groundwater production rates at each sampling point were determined by pumping until the water level in the casing stabilized, usually about 5 to 10 minutes. The rate at which the water was being pumped after stabilization was considered the production rate.

Sampling points were allowed to sit for at least 24 hours following development or extended pumping prior to making water level measurements or collecting samples.

Water levels were determined in the sampling points and in wells with a Heron Instruments Skinny Dipper water level sensor. Water levels were measured at well 1049 with an In Situ Model PXD-261, 15-psi transducer calibrated with the hand-held water level sensor. Water level measurements are accurate to about 0.02 ft. Water levels in well 1049 were collected at 5-minute intervals and transmitted to the SOARS system for real-time display and analysis.

Groundwater samples were collected using a peristaltic pump. Analysis methods are described in the *Environmental Sciences Laboratory Procedures Manual* (S04343). Prior to sample collection, a YSI 556MPS multiprobe system was suspended in each casing to make in-situ measurements of oxidation-reduction potential (ORP), pH, specific conductance, and temperature (S04343, methods AP[ORP-1], AP[pH-1], and AP[EC-1]). For sampling, groundwater was pumped through an in-line 0.45 micrometer filter (QED Environmental Systems Quick Filter Model FF8200T) to remove suspended sediment. At least 200 milliliters (mL) of sample was pumped through the filter before collecting the sample to minimize possible adsorption to the filter. Alkalinity was measured in the field on filtered samples by titration with sulfuric acid (S04343, method AP[Alk-1]). Samples were collected in plastic bottles. Samples for cations and metals were preserved in the field by acidification with concentrated nitric acid to pH <2. All samples were kept on ice until laboratory analysis. Calcium, magnesium, potassium, and sodium were analyzed by flame atomic absorption (S04343, methods AP[AA-1], AP[Ca-1], AP[Mg-1], AP[K-1], and AP[Na-1]). Chloride, nitrate, and sulfate were analyzed by ion chromatography (S04343, methods AP[Cl-2], AP[NO_3-4], and AP[SO_4-4]). Ammonia was analyzed by colorimetry (S04343, method AP[NH_3-4]), and uranium by kinetic phosphorescence (S04343, method AP[U-2]). All chemical analyses except selenium were performed in LM's Environmental Sciences Laboratory. Selenium analyses were conducted at a contract laboratory by inductively coupled plasma–mass spectrometry (ICP-MS).

Loess samples were collected from borings AH-05, AH-06, and AH-07. Samples were obtained using the same hand-coring equipment described for sample point installation. Samples from 1-ft intervals were placed in plastic bags. A portion of each sample was oven dried at 80 °C for 24 hours, and another portion was air dried. Splits were made for analysis by homogenizing the sample and separating with a laboratory scoop. A 0.5 gram (g) split of the oven-dried sample was digested in 50 mL of concentrated nitric acid in a microwave digestion oven (S04343, procedure SE[MD-1]). A 2-g split of the air-dried portion was batch leached with 200 mL of deionized water (S04343, procedure CB[BT-1]). The leachates from the microwave digestion were analyzed for uranium; and deionized water leachates were analyzed for calcium, chloride, nitrate, potassium, sodium, sulfate, and uranium in the Environmental Sciences Laboratory using the same procedures as listed above for groundwater samples. Digestates were sent to a contract laboratory for analysis of selenium by ICP-MS. Concentrations were converted to micrograms of analyte per gram of dried loess.

Elevations were measured on the outcrop at the contact between the loess or alluvium/colluvium and Mancos Shale to determine the presence of channels on the bedrock that might influence groundwater migration. Elevations were determined using a survey-grade level and stadia rod. All elevations are referenced to the top of casing at well 1049, a point that was surveyed previously by a contract surveyor and is consistent with surveys for the rest of the Shiprock site.

A network of temporary survey stations was established, and the level survey loop was closed at each station. All outcrop elevation data have the G prefix.

6.0 Results

6.1 Groundwater Surface at the Loess-Mancos Contact

All sampling points except one (EF-25) are completed in groundwater at the loess-Mancos Shale contact. EF-25 was dry but was completed as a sampling point given the possibility that groundwater levels may rise. Seven borings (AH designations) were dry and were not made into sampling points. The AH borings were used for geologic control, to sample the loess, and to place some limits on the extent of the groundwater system.

Groundwater occurred in Tributary 1 as far south as sampling point EF-19 (see Figure 3). At 0.211 gallon per minute (gpm), sampling point EF-19 had one of the highest water production rates (Table 3). A boring (AH-04) about 80 ft southwest of EF-19 tagged Mancos Shale at about 5.2 ft below ground surface but did not encounter groundwater. Sampling point EF-19 was unusual in that it was bored in the tributary floor on a circular mound about 0.5 ft high covered by efflorescence (Figure 15).

All sampling points other than EF-19 that had production rates greater than 0.2 gpm (EF-4, EF-21, EF-22, and EF-24) were shallow and located in the East Fork streambed 15 to 100 ft upstream of the area with flowing seeps at the confluence of East Fork and the main course of Many Devils Wash. Sampling points between this area and EF-19 had lower production rates, some significantly lower.

The highest point of the groundwater surface was at sampling point EF-19. The groundwater surface generally follows the bedrock topography, decreasing in elevation as the Mancos Shale bedrock surface decreases in elevation to the north-northeast (Figure 16). Groundwater flow is generally in a northerly direction on top of the bedrock. The loess unit has thin gravel layers within it, and typically, a gravel layer is at or near the base of the loess. It appeared that sampling points having a recognizable basal gravel layer produced more groundwater than borings with only loess; however, this relationship is uncertain given that identification of the gravel layers was difficult during hand coring.

The groundwater surface drops about 7 ft between sampling point MD-1 and well 1049. Figure 16 shows the extent of the groundwater saturation at the loess-Mancos contact as defined by the sampling points installed during this study and borings drilled by Geoprobe in 1999. Because these sets of data were collected at different times, it is possible that areas depicted as dry in 1999 may now have groundwater.

Seepage occurs along the wash at the confluence of East Fork with Many Devils Wash and at a line of seeps starting at the knickpoint and extending northward for about 400 ft (Figure 16). Seepage in these two areas has been continuous since being visually monitored for at least a decade. Flow rates have not been measured but are estimated to average about 0.5 gpm from East Fork seeps and about 1 gpm from the knickpoint seeps.

Table 3. Water Production Rates (April) and Depth to Water (ft), Year 2010

Sampling Point ID	Production (gpm)	DTW Mar 12	DTW Mar 17	DTW Apr 23	DTW Apr 28
EF-01	0.079	3.44	3.45	3.48	3.49
EF-02	0.079	3.34	3.36	3.35	3.35
EF-03	<0.026	2.66	2.66	2.76	2.76
EF-04	0.238	2.46	2.47	2.5	2.76
EF-05	0.026	3.47	3.48	3.55	3.56
EF-06	0.053	3.37	3.37	3.44	3.46
EF-07	0.079	1.84	1.86	1.89	1.89
EF-08	<0.026	3.91	3.07	4.25	3.17
EF-09	0.079	3.63	3.66	3.68	3.69
EF-10	<0.026	1.99	1.98	2.04	2.04
EF-11	0.026	4.12	4.13	4.17	4.19
EF-12	0.026		7.32	7.14	5.74
EF-13	<0.026		6.46	6.25	6.25
EF-14	0.026		7.30	6.55	5.37
EF-15	0.026		6.75	6.58	5.46
EF-16	0.026		6.23	6.38	5.68
EF-17	0.026		6.63	6.63	6.62
EF-18	<0.066		7.08	7.07	7.07
EF-19	0.211		8.35	8.42	8.42
EF-20	0.132		6.23	6.27	6.29
EF-21	~0.238			2.64	2.64
EF-22	~0.238			4.05	4.05
EF-23	0.026			3.27	3.35
EF-24	~0.238			1.94	1.94
EF-25	dry				
MD-01	0.132			5.05	5.05
MD-02	<0.026			7.18	7.20
MD-03	<0.026			7.33	7.11
MD-04	<0.026			9.73	9.64

DTW = depth to water

Figure 15. Sampling Point EF-19 Showing Mound Covered by Efflorescence on Ground Surface

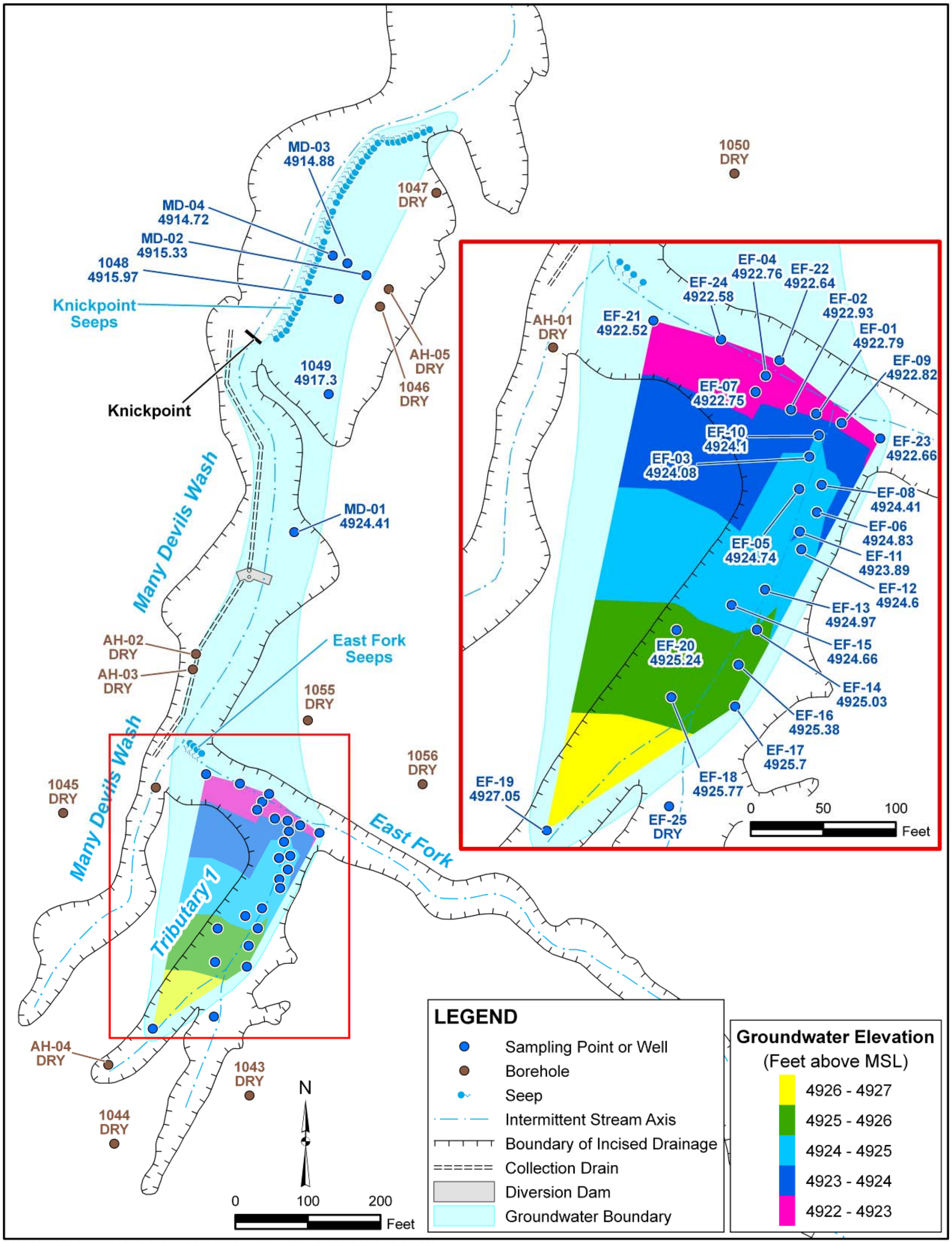

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Figure 16. Groundwater Elevation Contour Map in Tributary 1, April 27 and 28, 2010 (blue shaded area shows the limits of groundwater saturation based on existing data)

Well 1049 is located about 90 ft southeast of the knickpoint seeps; thus, the groundwater level likely correlates with the amount of water flowing at the seeps. Maximum variation in groundwater levels since February 2000 is 3.6 ft (Figure 17). Other than one high value measured on June 27, 2006, the maximum variation is 2.1 ft, and since the SOARS system was installed in July 2009, the levels have varied by less than 0.5 ft. The high value on June 27, 2006, is not associated with a rain event; thus, it may have been a measurement error.

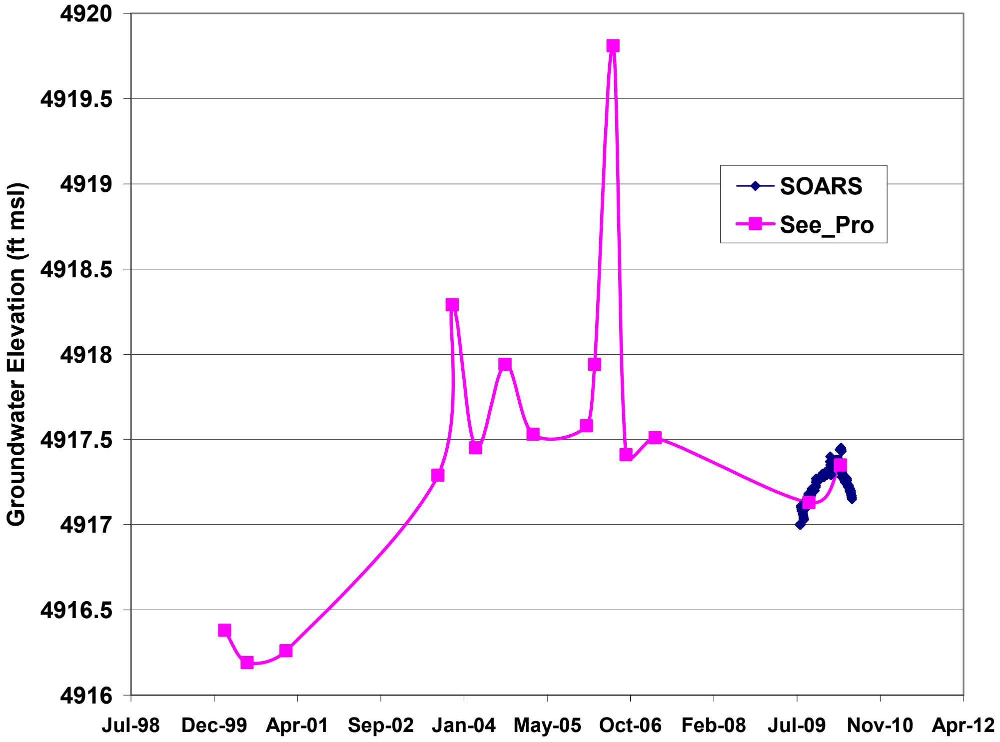

Figure 17. Groundwater Elevations in Well 1049
(Manual measurements are from LM's SEEPro database, datalogger measurements are from SOARS)

6.2 Groundwater Chemistry

Samples were collected from the EF and MD sampling points on April 27 and 28, 2010, and a complete set of analytical data is provided in Appendix A. The samples were remarkably similar in composition with only a few exceptions. Selenium concentrations ranged from 370 to 1,800 µg/L with a mean of 1,228 µg/L (Figure 18). Most values were near or slightly higher than the mean except at five points along the east side of Tributary 1 with values less than 850 µg/L. Uranium concentrations ranged from 133 to 165 µg/L with a mean of 147 µg/L (Figure 19). There is little variability in the distribution of uranium, and few points were more than one standard deviation (8 µg/L) removed from the mean. Nitrate (as NO_3) concentrations ranged from 2,157 to 3,087 mg/L, with a mean of 2,494 mg/L (Figure 20). The nitrate concentrations are fairly uniform, with the lowest and the highest values occurring in the same general area of East Fork. Sulfate concentrations ranged from 16,524 to 20,315 mg/L with a mean of 17,318 mg/L (Figure 21). The distribution of sulfate is also rather uniform. The similarity of major ion chemistry is demonstrated on a Piper diagram (Figure 22). The groundwater data from all the sampling points plot in a small area on the Piper diagram. The groundwater is dominated by sodium sulfate with a mean total dissolved solids content of 27,796 mg/L.

6.3 Chemistry of Loess Samples

A preliminary assessment of concentrations of contaminants in loess at Many Devils Wash was made by analyzing 13 samples collected with a hand coring device. Each sample consisted of a split representing a 1-ft interval. Extractions were made using two different methods—agitation with deionized water, and microwave digestion with concentrated nitric acid. The results from borings AH-06 and AH-07 are plotted as one set (called AH-06,07), because they are in the same general area and represent different stratigraphic levels within the loess. Complete results of the loess chemistry are presented in Appendix B.

Uranium concentrations in all but two samples were less than the detection limit. The two samples that had detectable uranium had values of 0.06 microgram per gram (µg/g), just above the detection limit of 0.04 µg/g for the deionized-water-leached analyses. None of the microwave-digested samples had uranium concentrations above the detection limit; the detection limit was 1 µg/g for all but two samples, for which the detection limit was 1.6 µg/g.

Selenium concentrations in the loess samples ranged from 0.022 to 2.5 µg/g with a mean of 0.62 µg/g. In all samples, more selenium was extracted using nitric acid than deionized water (Figure 23). Only one sample, AH-05 at 2 ft, had a selenium concentration that exceeded 1 µg/g. The highest selenium concentrations were in samples from boring AH-05, located near the knickpoint seeps. Concentrations of selenium were less than 1 µg/g at all depths in borings AH-06,07, which are located upstream of any known contamination.

Nitrate (as NO_3) and sulfate were analyzed in the deionized water extractions but not in the nitric acid digestions. Nitrate concentrations ranged from 130 to 2,160 µg/g (Figure 24) and sulfate ranged from 1,910 to 29,090 µg/g (Figure 25) in loess samples from borehole AH-05. Concentrations were lower in samples from upstream locations AH-06,07; nitrate ranged from 50 to 230 µg/g, and sulfate ranged from 270 to 12,600 µg/g.

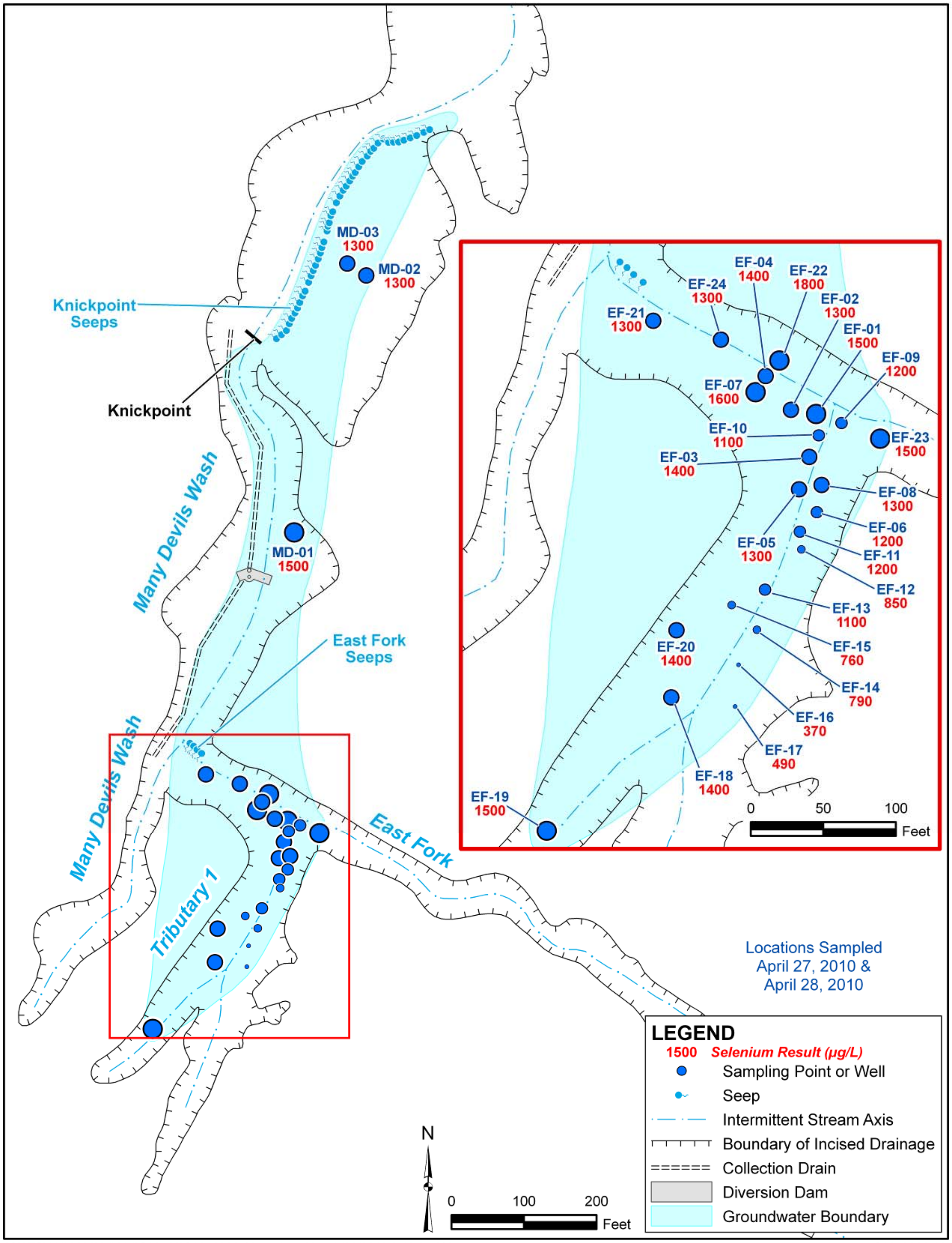

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Figure 18. Groundwater Selenium Concentrations April 27 and 28, 2010
Magnitude reflected by dot size.

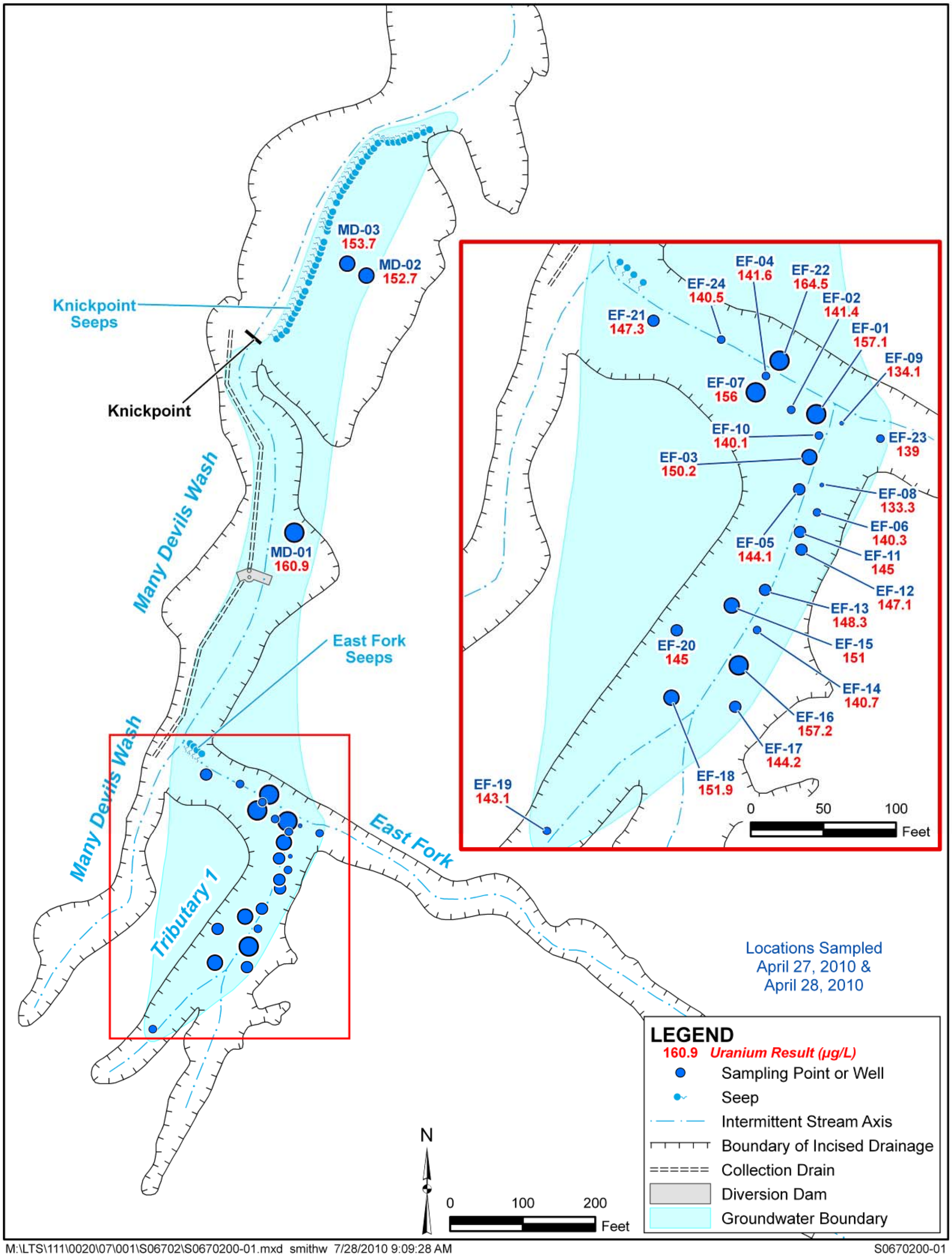

Figure 19. Groundwater Uranium Concentrations April 27 and 28, 2010
Magnitude reflected by dot size.

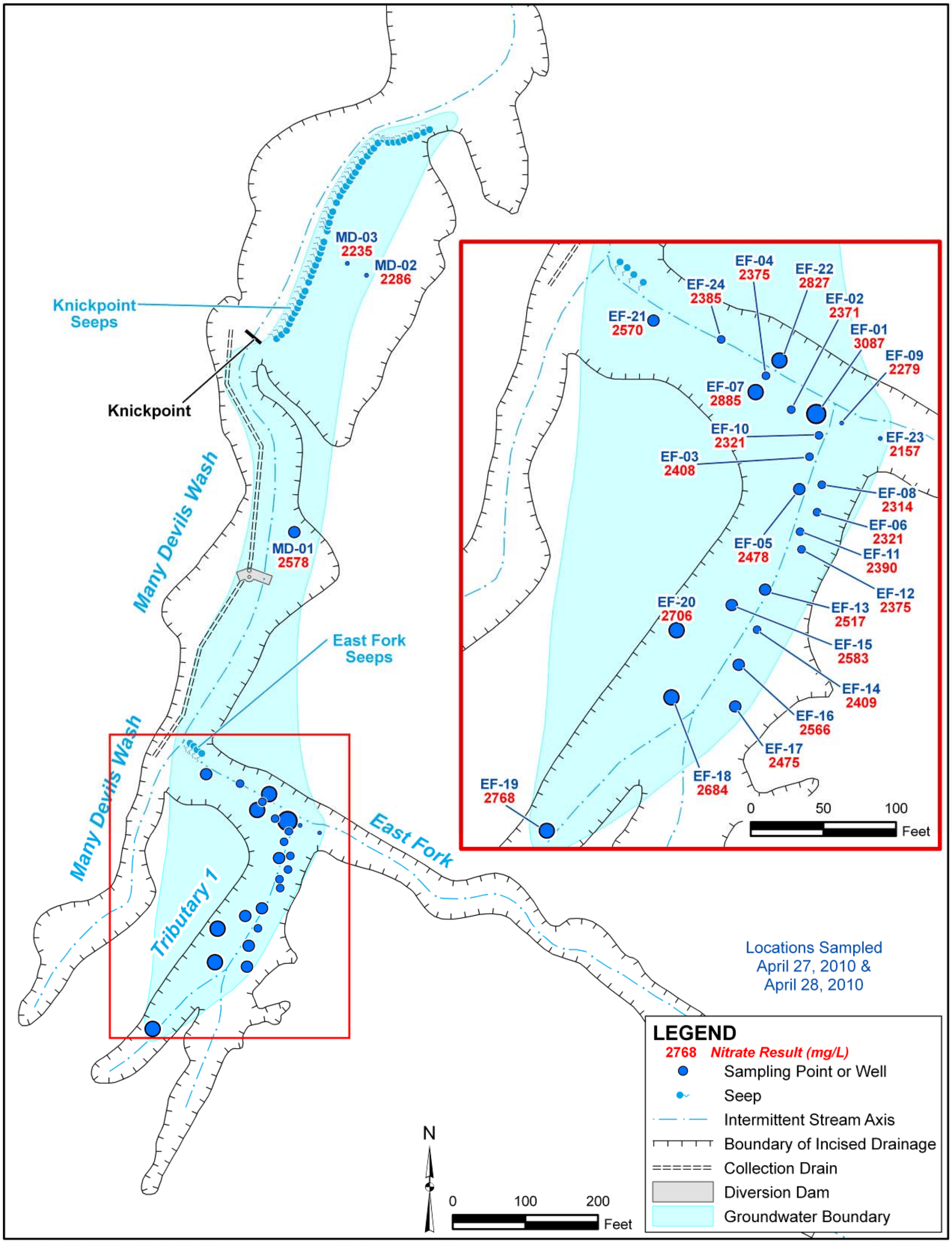

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Figure 20. Groundwater Nitrate (as NO_3) Concentrations April 27 and 28, 2010
Magnitude reflected by dot size.

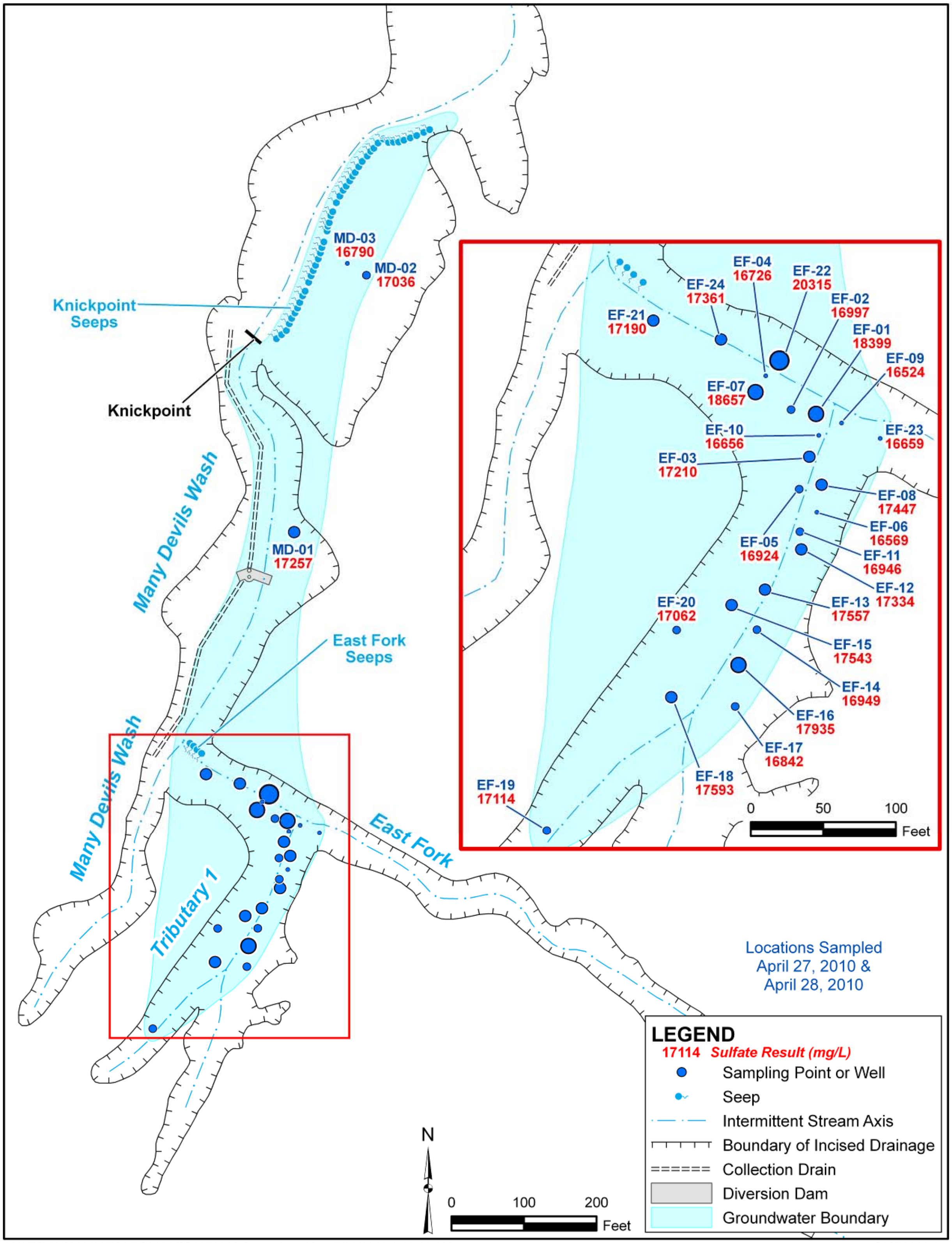

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Figure 21. Groundwater Sulfate Concentrations April 27 and 28, 2010
Magnitude reflected by dot size.

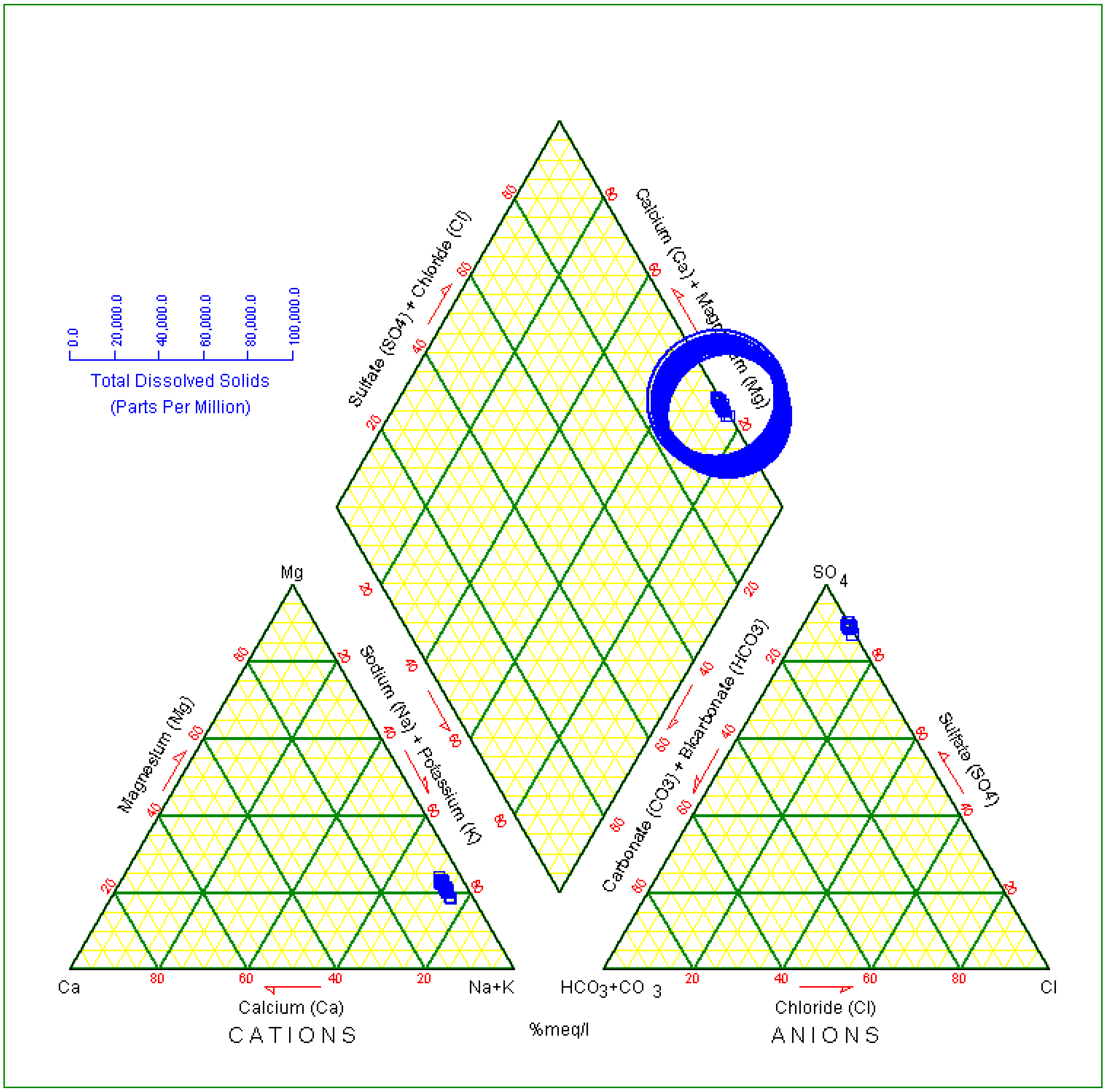

Figure 22. Piper Diagram of Groundwater from EF and MD Points Sampled April 27 and 28, 2010 (The radii of the blue circles on the diamond portion of the diagram display the total dissolved solids content.)

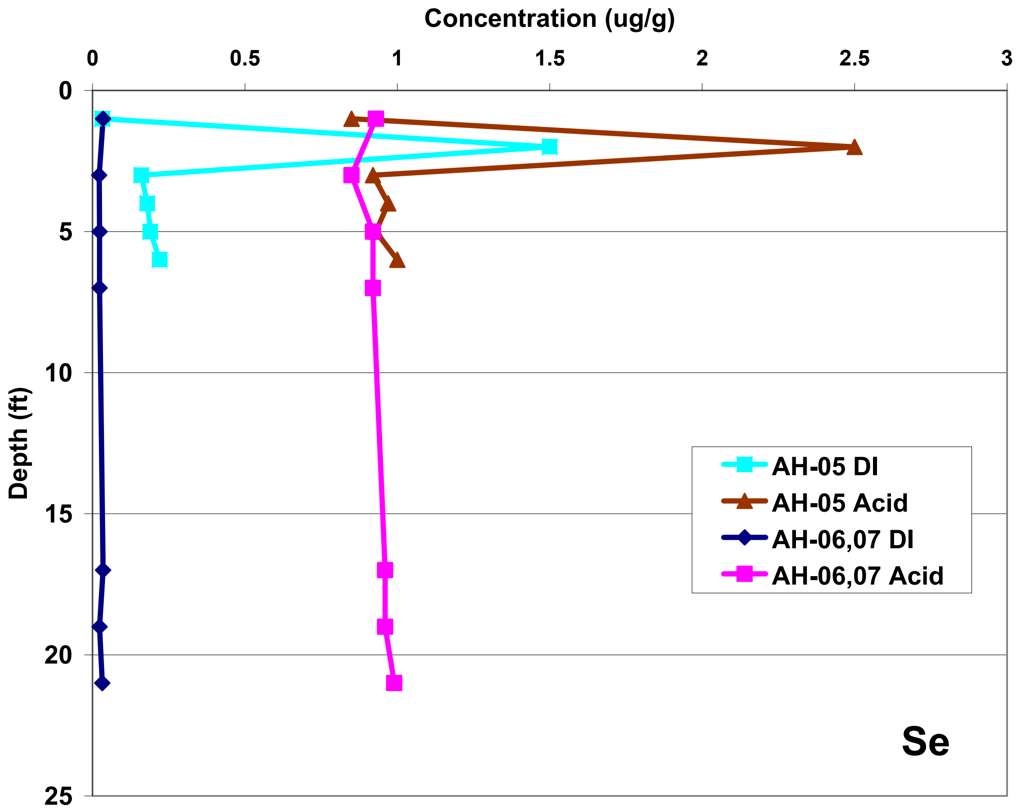

Figure 23. Selenium Concentrations with Depth in Loess at Locations AH-05 and AH-06,07 (DI - deionized water extraction, Acid = nitric acid microwave digestion)

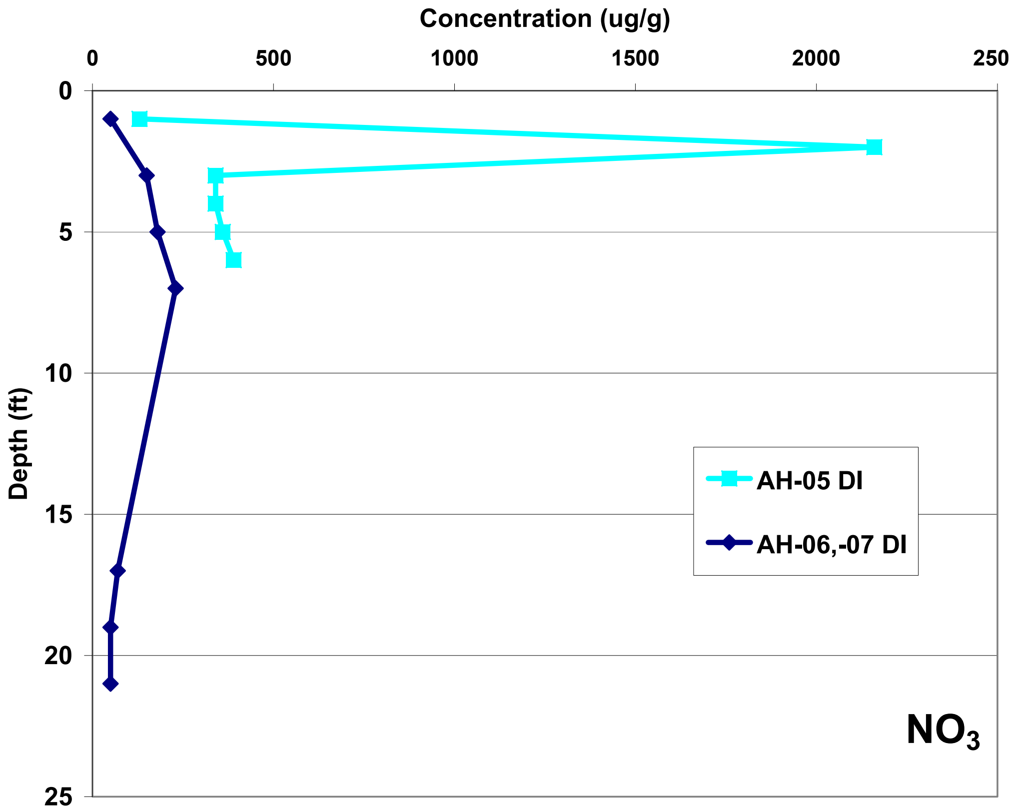

Figure 24. Nitrate Concentrations with Depth in Loess at Locations AH-05 and AH-06,07 (DI - deionized water extraction)

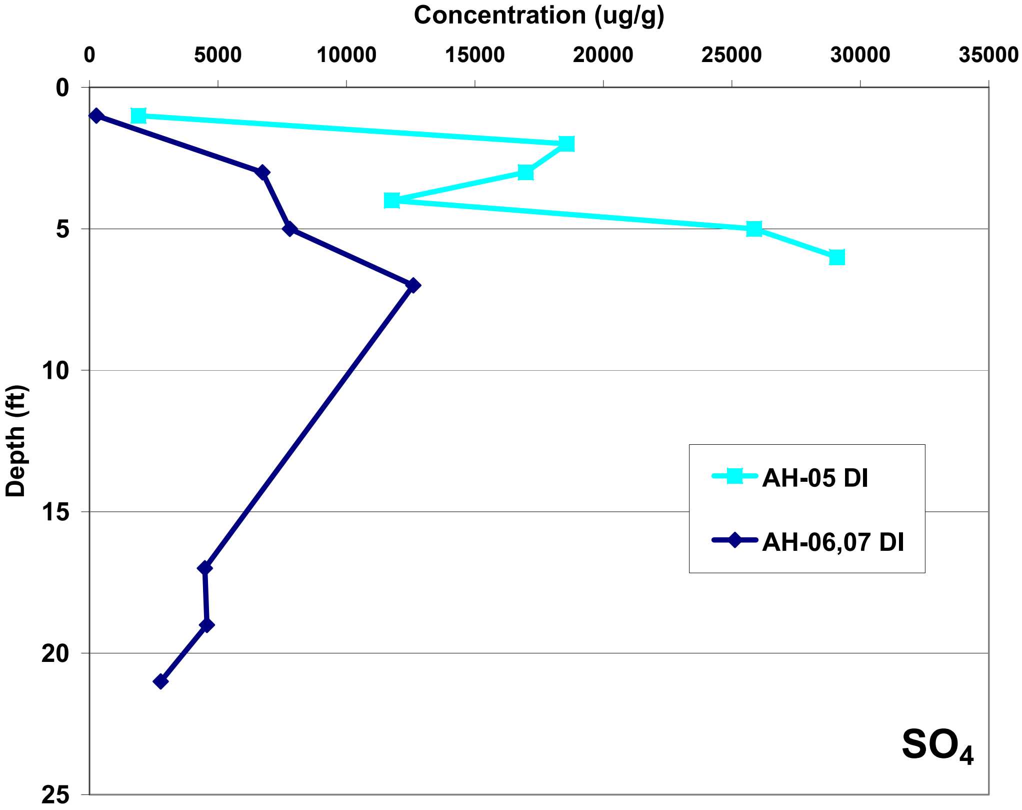

Figure 25. Sulfate Concentrations with Depth in Loess at Locations AH-05 and AH-06,07 (DI - deionized water extraction)

7.0 Discussion

Many Devils Wash drains an area of 11.5 square miles near DOE's disposal cell built for containment of uranium mill tailings. In the 1,800-ft stretch above its confluence with the San Juan River, surface water in the wash and seepage entering the wash have high concentrations of nitrate, selenium, sulfate, and uranium. Previous DOE documents indicate that these constituents are contaminants from the former milling operation; however, the occurrence of the seeps on the opposite (east) side of the wash and other factors are difficult to explain assuming the mill site as the source of contamination. The groundwater surface feeding the seeps at the knickpoint has been at a nearly constant elevation, as evidenced by the groundwater elevation in well 1049. Prior to this study, observations at East Fork and Tributary 1, the farthest upgradient expression of water in the wash, suggested that all of the groundwater feeding Many Devils Wash might be originating at a single location in Tributary 1. In this investigation, the groundwater in Tributary 1 was tracked as far as was possible using hand coring methods to provide additional data relating to the origins of the high concentrations of contaminants.

Prior to this study, perennial groundwater seepage was observed at the mouth of East Fork where it enters Many Devils Wash. During occasional high-water events, a small amount of seepage had also been observed at the mouth of Tributary 1 where it enters East Fork and along the 200-ft stretch of East Fork from Tributary 1 to the confluence with Many Devils Wash. Although no water had been observed in Tributary 1, efflorescence had been observed as far as 100 ft south from its confluence with East Fork. This investigation was the first to detect groundwater in Tributary 1 and found that it extends at least 200 ft farther south than the efflorescence. Twenty-four hand cored sampling points were installed in Tributary 1 and East Fork. All but two of the penetrations (EF-25 and AH-04) intercepted groundwater. Although the two dry penetrations help define boundaries of the groundwater surface, it is possible that flow is channelized and that the groundwater surface extends still farther south. Determination of the southern extent of groundwater requires drilling to depths unreachable by hand coring.

The farthest south sampling point (EF-19) had one of the highest groundwater production rates, suggesting that the southern terminus of groundwater saturation was not reached. Of interest, EF-19 was located on a small (5-ft-diameter) mound of loess caked with efflorescence referred to as a blister. Although not certain, it seems like the formation of this mound is related to the high groundwater surface, perhaps caused by swelling clays. Other features resembling these mounds are found in East Fork between the mouth of Tributary 1 and Many Devils Wash, and in a broad "mounded" area about 400 ft south of the incised channel of Tributary 1 (Figure 13). These features may be related to erosion features formed by groundwater sapping as described by Leopold et al. (1964). Groundwater sapping involves the undercutting of steep-walled arroyos by shallow groundwater and may explain the deeply incised loess channeling in Many Devils Wash and its tributaries. Thus, groundwater in the EF-19 area may originate from percolation through the upgradient loess deposits, movement along the loess-Mancos Shale contact, and emergence in this region of headward erosion of the tributary channels. Alternatively, some or all of the groundwater at EF-19 could be entering from below through fracture flow in the Mancos Shale. For this groundwater to be derived from the tailings area, it may travel deep within the Mancos Shale through fractures and resurface along vertical fractures at unpredictable locations; one such vertical fracture may intercept the loess in Tributary 1. Once the groundwater is in the loess it travels along the loess – Mancos Shale contact to the seepage areas in Many Devils Wash.

The groundwater chemical compositions in all 24 sampling points in East Fork and Tributary 1 are remarkably similar, indicating a common source. Major ion compositions plot in the same location on a Piper diagram (Figure 22). Nitrate, selenium, and sulfate concentrations were similar in the new sampling points and similar to the MD sampling points near the knickpoint. These chemical similarities indicate that the groundwater in the upgradient area at Tributary 1 could be a source, perhaps the only source, feeding the seeps and surface water in Many Devils Wash. Detailed mapping of the geologic contact between Mancos Shale bedrock and loess or alluvium/colluvium indicates that paleochanneling in the bedrock may direct groundwater flow from Tributary 1 to the knickpoint seeps.

Samples of loess were analyzed to evaluate loess as a potential natural source for some or all of the nitrate, selenium, sulfate, and uranium observed in Many Devils Wash. Samples were collected from three locations, AH-05 near the knickpoint, and AH-06 and AH-07 located upgradient of Tributary 1 (locations are shown on Figure 3 and Figure 4). The samples at AH-05 have higher concentrations of all constituents, particularly in the upper strata, and the ground surface in this area contains efflorescence. It is likely that shallow sediments in this area are derived in part from local windblown and flood-stage contamination related to Many Devils Wash. The molar concentration of sulfate is similar to that of calcium, suggesting the presence of gypsum in the sediment. Because of the probable influence from local contamination, the chemical results from the AH-05 loess samples are not discussed further.

The concentrations of nitrate, selenium, sulfate, and uranium in the upgradient loess samples from AH-06 and AH-07 leached with deionized water represent the labile fractions of these constituents that are readily available to enter the groundwater system. The mean concentrations of nitrate, selenium, sulfate, and uranium in the water soluble portion of these samples were 111, 0.03, 5,604, and 0.04 µg/g, respectively. These results suggest that the loess is not particularly enriched in these constituents. However, this study was preliminary in two respects: (1) the extractions for nitrate and sulfate only remove the most labile portion of these constituents, and (2) the paucity of samples prevents a full characterization of the distribution of these constituents in the loess deposits.

8.0 Conclusions

Detailed geologic mapping defined the contact between loess valley fill and Mancos Shale. The mapping shows a channel that could be a pathway for groundwater to migrate from the Tributary 1 area northward to the knickpoint seeps. However, because much of the potential pathway is obscured by loess deposits too thick to hand core, details of the bedrock erosional contact are not available in some critical areas.

This study better defined the extent of the groundwater surface upgradient of the exposures of contaminated water in Many Devils Wash. Groundwater extends at least 350 ft southward up Tributary 1. The farthest upgradient sampling point (EF-19) intercepted a relatively productive portion of the groundwater, and it is postulated that the groundwater surface may extend even farther south. The groundwater elevation in EF-19 was 4,927.05 ft. This elevation is about 16 ft lower than the groundwater in well 0812 located in the "sump" area to the south of the disposal cell, indicating that a gradient exists between contaminated groundwater at the former mill site and the highest point of the groundwater surface in the Many Devils Wash area. Thus, if a pathway were available through the Mancos Shale, groundwater could flow from the sump area to the Many Devils Wash area.

The groundwater chemistry in all 24 EF sampling points was remarkably similar and was similar to that in seeps and in the MD sampling points near the knickpoint. The commonality of chemical signatures suggests a common source for the groundwater and seep water. This common source could be centered near sampling point EF-19 or could be further south.

Preliminary analyses of soil concentrations in loess were inconclusive in determining if loess is a source for contamination to groundwater. The samples had relatively low levels of nitrate, selenium, sulfate, and uranium, suggesting the loess is not the source of these constituents.

Probably the most prevailing issue regarding the contamination at Many Devils Wash is defining the source of the contamination. One hypothesis maintains that the contamination is from the former milling operation and has reached Many Devils Wash by flowing through the Mancos Shale bedrock under Many Devils Wash and then upward to the base of the loess on the east side, perhaps in the Tributary 1 area. An alternate hypothesis maintains that the contamination is from naturally occurring processes similar to those in other areas underlain by Mancos Shale bedrock that have high concentrations of nitrate, selenium, and other constituents in the groundwater (Butler and Leib 2002; Tuttle et al. 2007; Thomas et al. 2007; Holloway and Smith 2005). In these published studies from other field sites, concentrations of selenium and sulfate from Mancos Shale seeps are reported that exceed those at Many Devils Wash; however, uranium and nitrate are not well studied. DOE is currently conducting a study of natural contamination in Mancos Shale groundwater throughout much of its depositional basin.

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Appendix A

Groundwater Chemistry Data Measured During this Study

Sampling Point	Sampling Date/Time	Temp °C	Sp. Cond. µS/cm	Cond. µS/cm	DO mg/L	pH	ORP mV	Alkalinity as $CaCO_3$, mg/L	Color	Ca mg/L	Na mg/L	K mg/L	Mg mg/L	NH_3 mg/L	Cl mg/L	NO_3 (as NO_3 mg/L	SO_4 mg/L	U µg/L	Se µg/L	TOC mg/L
EF-01	3/12/2010	6.5	32460		5.9	7.94	127.5													
EF-01	3/13/2010	6.5	33290		6.2	7.78	166.2													
EF-01	3/18/2010	7.08	33140	21817	7.1	7.93	173.1													
EF-01	4/28/2010	11.75	33360	24920	3.67	7.73	179	580	181	440	7700	33.5	1300	1	1922	3087	18399	157.1	1500	54
EF-02	3/12/2010	6.18	30130		5.6	7.71	129.3													
EF-02	3/13/2010	6.15	29830		6.2	7.57	164.1													
EF-02	4/28/2010	11.11	29625	21770	3.3	7.41	175	590	87	444	7100	29	1200	1	1460	2371	16997	141.4	1300	36
EF-03	3/12/2010	6.95	27890		6.4	7.63	133.5													
EF-03	3/13/2010	6.72	28650		6.9	7.53	170.2													
EF-03	4/28/2010	11.34	29988	22170	2.42	7.15	206	610	108	464	7000	31	1200	**1**	1493	2408	17210	150.2	1400	30
EF-04	3/12/2010	7.44	30490		7.3	7.93	123.7													
EF-04	3/13/2010	5.94	30000		7	7.7	159													
EF-04	4/28/2010	10.43	29976	21630	3.11	7.41	184	590	88	436	6900	30.5	1200	2	1470	2375	16726	141.6	1400	33
EF-05	3/12/2010	6.63	29620		4.5	7.58	152.1													
EF-05	3/13/2010	6.51	30000		5.3	7.51	173.3													
EF-05	4/28/2010	10.7	30078	21870	2.43	7.37	172	610	82	436	6900	30.0	1200	1	1464	2478	16924	144.1	1300	25
EF-06	3/12/2010	8.75	30640		4.1	7.58	151.8													
EF-06	3/13/2010	8.58	29230		4.4	7.46	173.3													
EF-06	4/28/2010	11.77	29300	21900	4.37	7.41	214	610	97	430	6900	27.5	1150	1	1452	2321	16569	140.3	1200	30
EF-07	3/12/2010	5.31	33430		6.8	7.84	130.2													
EF-07	3/13/2010	5.19	33400		9.7	7.76	157.4													
EF-07	4/28/2010	10.76	34131	24850	5.87	7.69	178	590	178	440	7800	30	1200	**1**	1664	2885	18657	156	1600	41
EF-08	3/12/2010	8.23	31940		2.2	7.75	150.1													
EF-08	3/13/2010	8.14	30700		2.8	7.65	170.7													
EF-08	4/28/2010	11.13	29831	21930	2.52	7.55	190	620	137	446	7000	28	1150	1	1457	2314	17447	133.3	1300	27
EF-09	3/12/2010	8.43	30110		3.8	7.64	134.2													
EF-09	3/13/2010	8.26	28940		4.6	7.55	170.4													
EF-09	4/28/2010	11.12	29383	21590	2.1	7.68	160	580	86	438	7000	26	1250	1	1501	2279	16524	134.1	1200	25
EF-10	3/12/2010	6.19	29300		3.4	7.66	132.7													
EF-10	3/13/2010	5.95	29680		4.1	7.44	172.8													
EF-10	4/28/2010	11.79	29624	22150	3.07	7.41	171	590	92	444	6800	28	1150	1	1439	2321	16656	140.1	1100	28
EF-11	3/12/2010	8.4	30660		4.4	7.66	176.3													
EF-11	3/13/2010	8.37	29530		4.4	7.45	176													
EF-11	4/28/2010	11.35	29193	21600	2.32	7.63	196	630	116	440	7300	27.5	1150	1	1479	2390	16946	145	1200	26
EF-12	3/18/2010	8.23	29320	19936	5.4	7.68	175.8													
EF-12	3/18/2010	9.65	30280	21414	4.7	7.76	156.6													
EF-12	4/28/2010	11.05	30174	22140	0.93	7.69	230	650	108	438	7100	28.5	1000	**1**	1484	2375	17334	147.1	850	74
EF-13	3/18/2010	8.47	30510	20880	4.4	7.61	158.8													
EF-13	4/28/2010	11.02	30102	22070	0.52	7.54	219	660	116	450	7700	29.5	1100	**1**	1465	2517	17557	148.3	1100	53
EF-14	3/18/2010	9.6	29620	20913	6.1	7.71	160													
EF-14	4/28/2010	11.32	29881	22070	0.86	7.62	199	650	105	438	7100	30.5	1000	**1**	1418	2409	16949	140.7	790	83
EF-15	4/28/2010	10.91	30265	22130	2.43	7.83	227	670	138	438	7200	32	950	**1**	1400	2583	17543	151	760	63
EF-16	3/18/2010	9.36	32250	22633	6.8	7.79	163													
EF-16	4/28/2010	11.5	31423	23320	0.44	7.83	195	720	122	440	7300	30	1100	**1**	1478	2566	17935	157.2	370	73
EF-17	3/18/2010	10.18	29310	21040	6.7	7.59	169.7													

Sampling Point	**Sampling Date/Time**	**Temp °C**	**Sp. Cond. µS/cm**	**Cond. µS/cm**	**DO mg/L**	**pH**	**ORP mV**	**Alkalinity as $CaCO_3$, mg/L**	**Color**	**Ca mg/L**	**Na mg/L**	**K mg/L**	**Mg mg/L**	**NH_3 mg/L**	**Cl mg/L**	**NO_3 (as NO_3 mg/L**	**SO_4 mg/L**	**U µg/L**	**Se µg/L**	**TOC mg/L**
EF-17	4/28/2010	11.7	29834	22260	2.24	7.7	206	660	102	426	7100	30.5	1100	**1**	1422	2475	16842	144.2	490	58
EF-18	3/18/2010	9.4	30330	21291	6.3	7.66	155.1													
EF-18	4/28/2010	10.75	30682	22330	0.91	7.43	207	660	116	430	7400	30.5	1100	**1**	1443	2684	17593	151.9	1400	42
EF-19	3/18/2010	8.23	30450	20702	5.3	7.39	163.1													
EF-19	4/28/2010	10.67	30621	22240	5.74	7.42	220		108	450	7800	36	1000	**1**	1342	2768	17114	143.1	1500	34
EF-20	3/18/2010	9.12	30110	20981	6.5	7.44	175.6													
EF-20	4/28/2010	11.52	30357	22540	4.4	7.48	224		145	432	7400	33	1150	1	1379	2706	17062	145	1400	38
EF-21	4/28/2010	12.32	30092	22800	1.92	7.33	179	610	99	416	7200	29.5	1050	**1**	1408	2570	17190	147.3	1300	34
EF-22	4/28/2010	10.88	36297	26510	2.11	7.07	188	690	148	422	7500	31.5	1300	1	1752	2827	20315	164.5	1800	50
EF-23	4/28/2010	10.98	29099	21310	3.72	7.5	153		89	432	6700	28.5	1100	**1**	1518	2157	16659	139	1500	35
EF-24	4/28/2010	10.8	29322	21370	2.09	7.29	178		81	436	7200	29	1100	**1**	1479	2385	17361	140.5	1300	31
MD-01	4/27/2010	11,58	31063	23100	2.92	7.26	218	610	150	444	7200	36.5	1150	**1**	1521	2578	17257	160.9	1500	49
MD-02	4/27/2010								92	432	6700	28	1100	**1**	1538	2286	17036	152.7	1300	109
MD-03	4/27/2010	11.68	29750	22170	5.97	7.66	239	550	86	454	6700	31	1100	**1**	1510	2235	16790	153.7	1300	123
MD-04	4/27/2010	11.1	30242	22210	7.43	7.86	176													

Legend:

Pink	Instrument was not Calibrated
Green	Reading drifting rapidly
Bold	Less than detection limit
TOC	Total Organic Carbon
ORP	Oxidation-Reduction Potential
Sp. Cond.	Specific Conductance (conductivity normalized to 25 °C)
µS/cm	microsiemens per centimeter
Cond.	Conductivity
Temp	Temperature
DO	Dissolved Oxygen

Appendix B

Loess Chemistry Data

Physical Properties							
Boring	Depth* (ft)	GMC Oven (%)	VMC Oven (%)	GMC Air (%)	VMC Air (%)	<2mm Oven (%)	<2mm Air (%)
AH-05	1	3.70	5.54	2.80	4.20	62.32	58.63
AH-05	2	5.80	8.70	4.81	7.22	53.36	53.49
AH-05	3	6.55	9.82	5.86	8.79	51.88	59.79
AH-05	4	7.30	10.94	5.75	8.63	46.92	49.10
AH-05	5	7.34	11.00	7.21	10.82	42.45	55.00
AH-05	6	10.08	15.13	8.57	12.85	56.38	58.76
AH-07	1	10.76	16.01	9.66	14.50	100.00	97.96
AH-07	3	3.77	5.66	2.67	4.01	98.00	100.00
AH-07	5	4.09	6.14	2.97	4.46	100.00	100.00
AH-07	7	4.37	6.55	3.04	4.56	100.00	100.00
AH-06	17	10.40	15.60	8.89	13.34	96.50	96.24
AH-06	19	4.35	6.52	3.24	4.86	97.95	98.11
AH-06	21	3.89	5.84	2.99	4.48	100.00	100.00

Notes

* For AH-06 and AH-07, depths relative to ground surface at AH-07

All soils are light gray-brown in color

All samples collected on 4/23/2010

With very aggressive disaggregation, all soils would be 100% <2mm

LOD	Loss on Drying
Oven	Oven dried at 90 °C
Air	Air dried
<2mm	Size fraction less than 2 mm
GMC	Gravimetric moisture content
VMC	Volumetric moisture content assuming bulk density of 1.5 g/cc

Microwave Digestion (Concentrated nitric acid) of oven-dried soils, 0.5 g in 50 mL
*** For AH-06 and AH-07, depths relative to ground surface at AH-07**

Boring	Depth* (ft)	Uranium (µg/L)	Uranium (µg/g)	Selenium (µg/L)	Selenium (µg/g)
AH-05	1	**10**	**1**	8.5	0.85
AH-05	2	**10**	**1**	25	2.5
AH-05	3	**10**	**1**	9.2	0.92
AH-05	4	**10**	**1**	9.7	0.97
AH-05	5	**10**	**1**	9.3	0.93
AH-05	6	**16**	**1.6**	10	1
AH-07	1	**10**	**1**	9.3	0.93
AH-07	3	**10**	**1**	8.5	0.85
AH-07	5	**10**	**1**	9.2	0.92
AH-07	7	**10**	**1**	9.2	0.92
AH-06	17	**10**	**1**	9.6	0.96
AH-06	19	**10**	**1**	9.6	0.96
AH-06	21	**16**	**1.6**	9.9	0.99
Means		10.92	1.09	10.54	1.05
Duplicates					
AH-05-06D	6	**16**	**1.6**	10	1
AH-06-05D	5	**10**	**1**	10	1
AH-07-07D	7	**10**	**1**	9.6	0.96

Bold values are detection limits.

Deionized Water (DI) Extraction of Air-dried Soils, 2 g. in 200 mL
*** For AH-06 and AH-07, depths relative to ground surface at AH-07**
D = duplicate analysis

Boring	Depth* (ft)	Uranium (µg/L)	Uranium (µg/g)	Calcium (mg/L)	Calcium (µg/g)	Sodium (mg/L)	Sodium (µg/g)	Potassium (mg/L)	Potassium (µg/g)	Chloride (mg/L)	Chloride (µg/g)	Nitrate (mg/L)	Nitrate (µg/g)	Sulfate (mg/L)	Sulfate (µg/g)	Selenium (µg/L)	Selenium (µg/g)
AH-05	1	0.6	0.06	10.2	1020	1.3	130	2.9	290	1	100	1.3	130	19.1	1910	0.32	0.032
AH-05	2	**0.4**	**0.04**	41.5	4150	16.4	1640	1.35	135	8.1	810	21.6	2160	185.7	18,570	15	1.5
AH-05	3	**0.4**	**0.04**	42.8	4280	11.6	1160	0.72	72	1.5	150	3.4	340	169.8	16,980	1.6	0.16
AH-05	4	**0.4**	**0.04**	32.1	3210	11.8	1180	0.74	74	1.6	160	3.4	340	117.7	11,770	1.8	0.18
AH-05	5	**0.4**	**0.04**	76	7600	12.6	1260	0.71	71	1.7	170	3.6	360	258.7	25,870	1.9	0.19
AH-05	6	**0.4**	**0.04**	82.8	8280	13.4	1340	0.68	68	1.8	180	3.9	390	290.9	29,090	2.2	0.22
AH-07	1	0.6	0.06	14.5	1450	0.36	36	0.71	71	**0.5**	**50**	0.5	50	2.7	270	0.35	0.035
AH-07	3	**0.4**	**0.04**	25.2	2520	0.69	69	0.88	88	**0.5**	**50**	1.5	150	67.3	6730	0.22	0.022
AH-07	5	**0.4**	**0.04**	26.9	2690	1.9	190	0.75	75	**0.5**	**50**	1.8	180	78	7800	0.23	0.023
AH-07	7	**0.4**	**0.04**	37.8	3780	2.45	245	0.8	80	**0.5**	**50**	2.3	230	126	12,600	0.23	0.023
AH-06	17	**0.4**	**0.04**	19.5	1950	0.49	49	1.23	123	**0.5**	**50**	0.7	70	44.9	4490	0.35	0.035
AH-06	19	**0.4**	**0.04**	19.9	1990	0.51	51	0.79	79	**0.5**	**50**	**0.5**	**50**	45.7	4570	0.23	0.023
AH-06	21	**0.4**	**0.04**	13.4	1340	0.67	67	0.66	66	**0.5**	**50**	**0.5**	**50**	27.7	2770	0.32	0.032
Means		0.43	0.04	34.05	3404.62	5.71	570.54	0.99	99.38	1.48	147.69	3.46	346.15	110.32	11,032.31	1.90	0.19
Means AH06,07		0.43	0.04	22.46	2245.71	1.01	101.00	0.83	83.14	0.50	50.00	1.11	111.43	56.04	5604.29	0.28	0.03
Duplicates																	
AH-05-06D		**0.4**	**0.04**	98.5	9850	13.6	1360	0.81	81	2.1	210	4.2	420	402.1	40,210	2.4	0.24
AH-06-05D		**0.4**	**0.04**	14.2	1420	0.59	59	0.66	66	**0.5**	**50**	**0.5**	**50**	30.8	3080	0.3	0.03
AH-07-07D		**0.4**	**0.04**	36.8	3680	2.5	250	0.85	85	**0.5**	**50**	2.3	230	121.4	12140	0.26	0.026

Bold values are detection limits.

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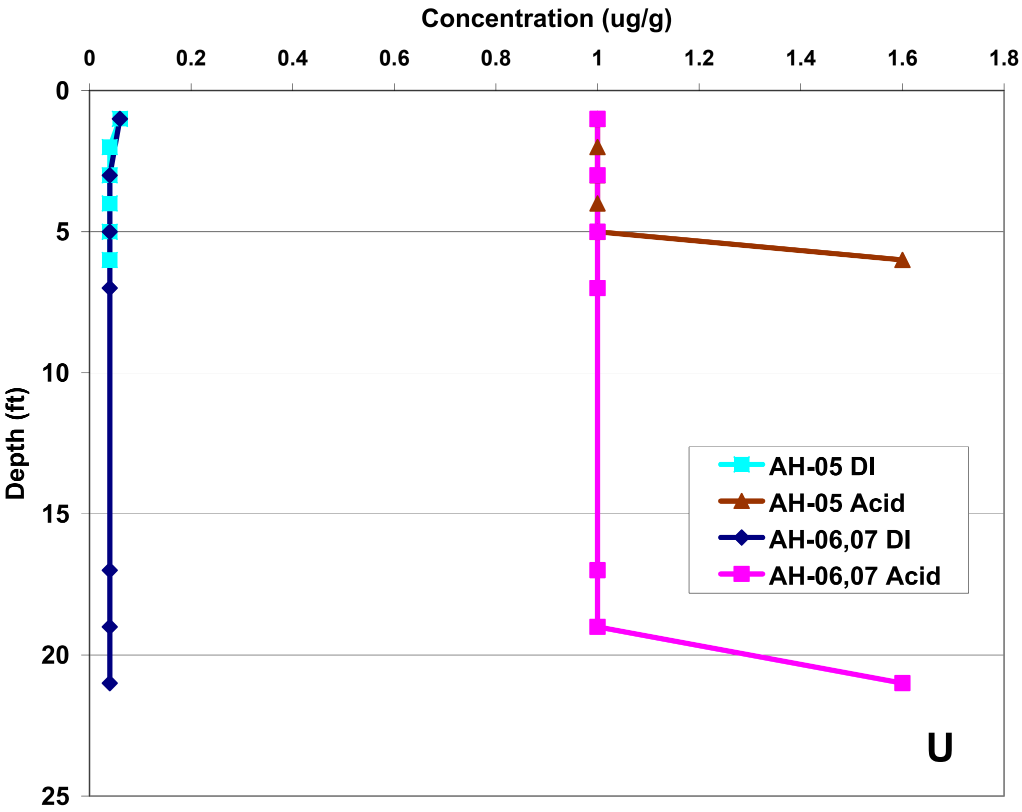
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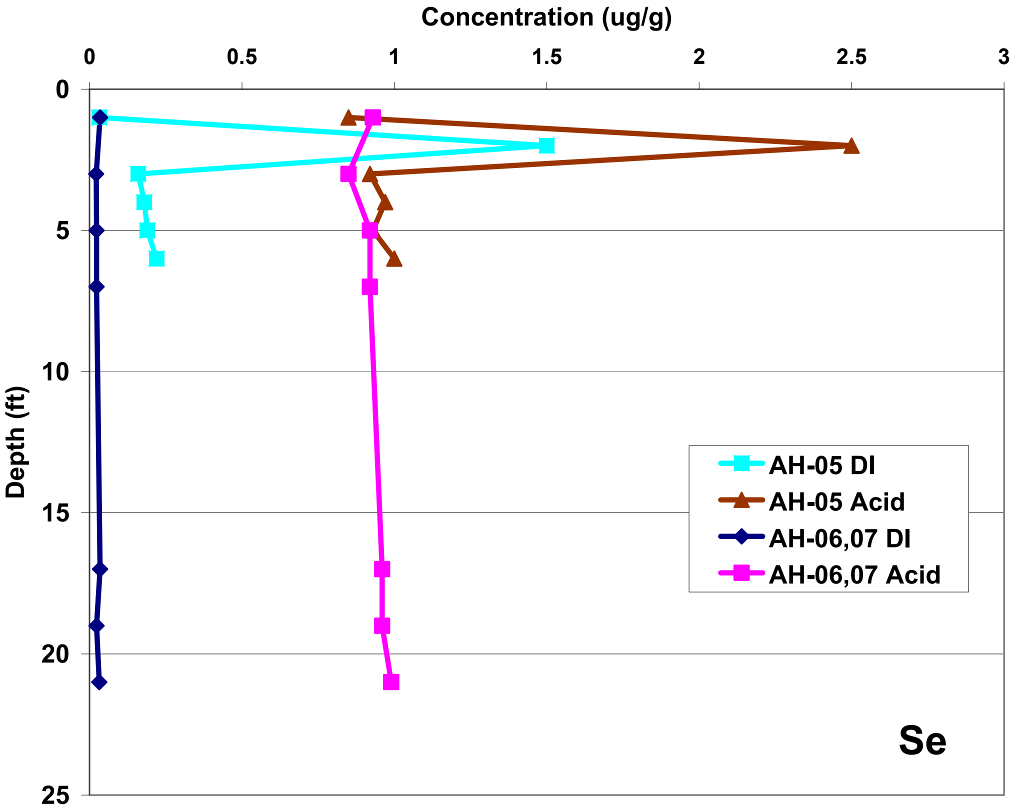
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Depth (ft)
0
5
10
15
20
25
AH-05 DI
AH-05 Acid
AH-06,07 DI
AH-06,07 Acid
U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0.5
1
1.5
2
2.5
3
Depth (ft)
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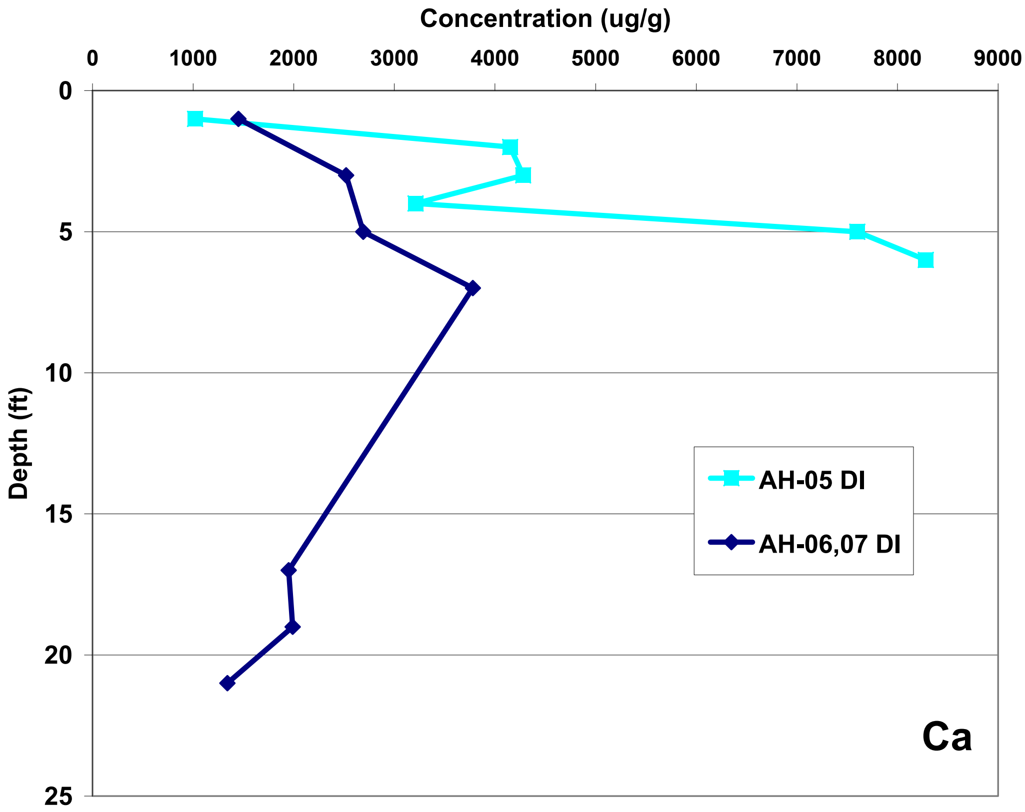
5
10
15
20
25
AH-05 DI
AH-05 Acid
AH-06,07 DI
AH-06,07 Acid
Se


Concentration (ug/g)
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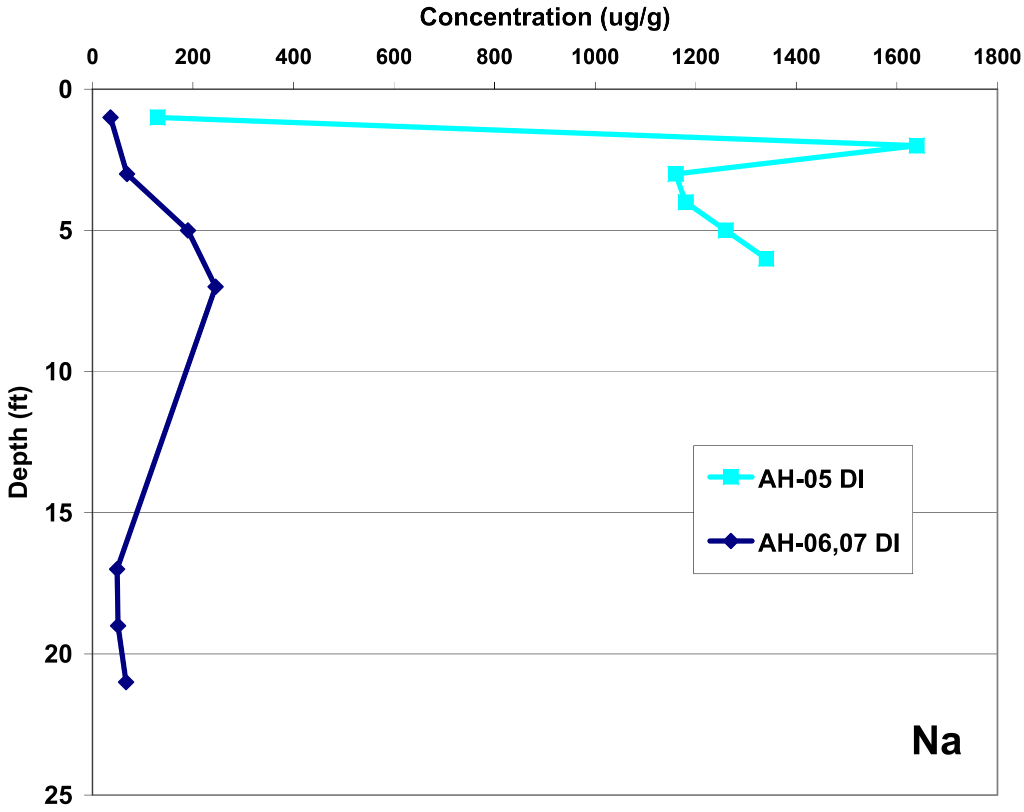
1000
2000
3000
4000
5000
6000
7000
8000
9000
Depth (ft)
0
5
10
15
20
25
AH-05 DI
AH-06,07 DI
Ca


Concentration (ug/g)
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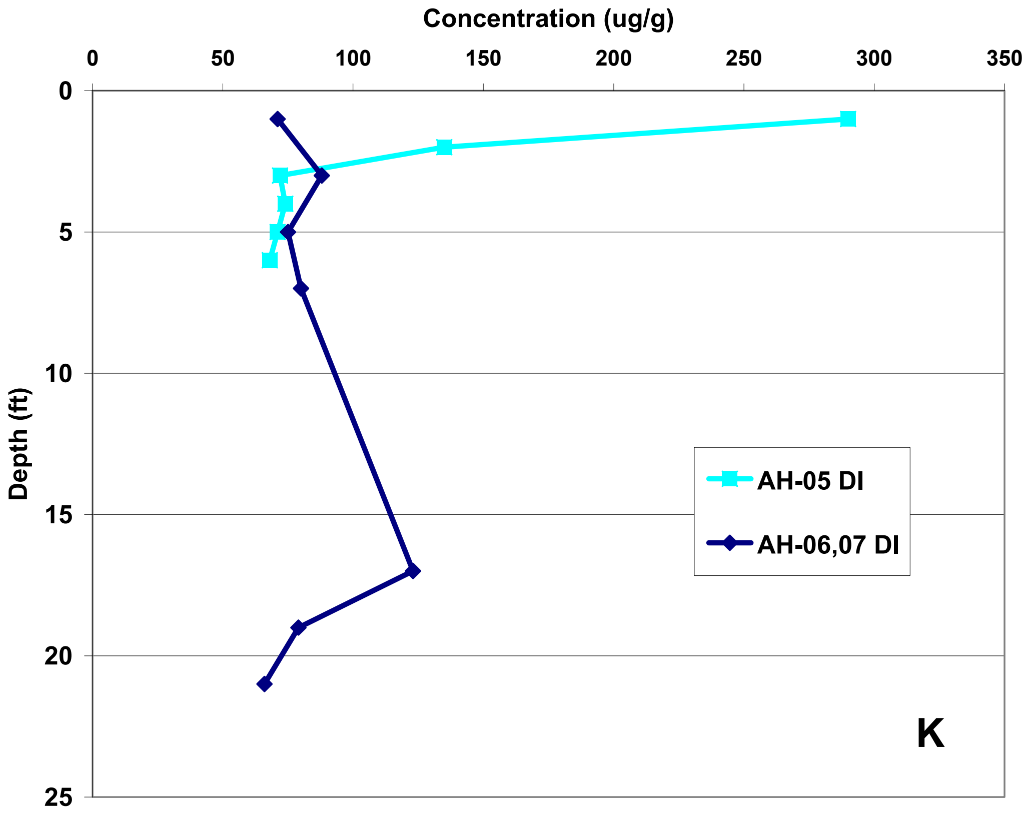
200
400
600
800
1000
1200
1400
1600
1800
Depth (ft)
0
5
10
15
20
25
AH-05 DI
AH-06,07 DI
Na


Concentration (ug/g)
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150
200
250
300
350
Depth (ft)
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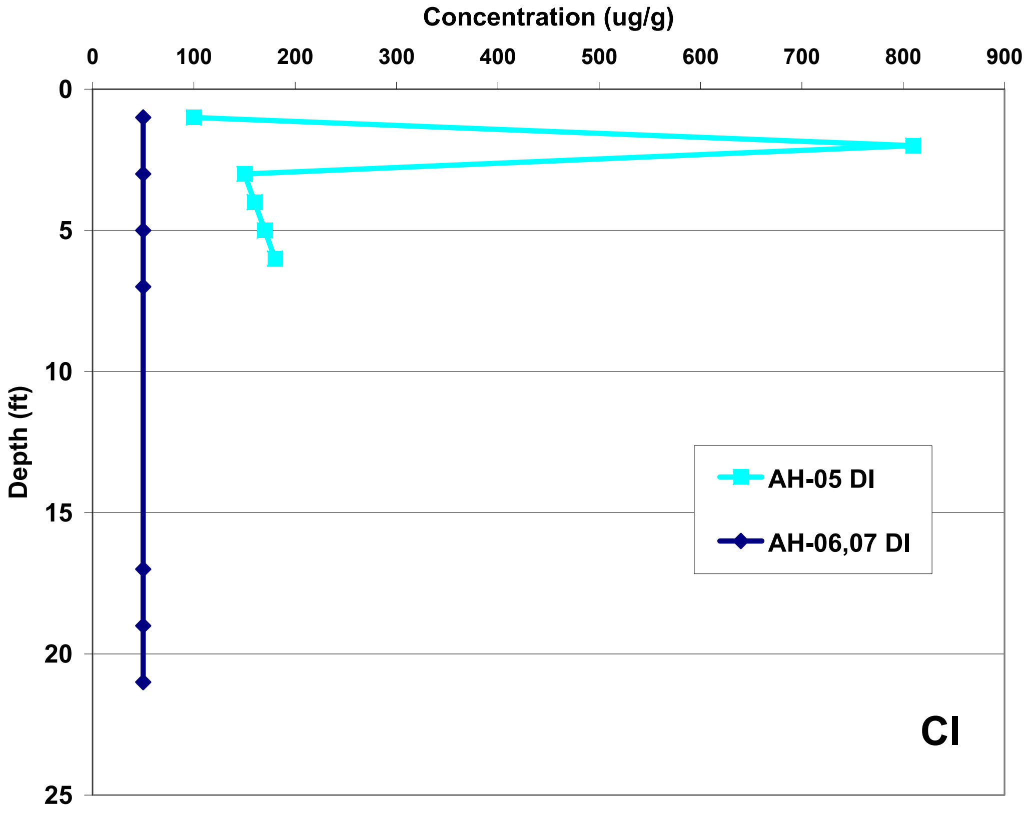
5
10
15
20
25
AH-05 DI
AH-06,07 DI
K


Concentration (ug/g)
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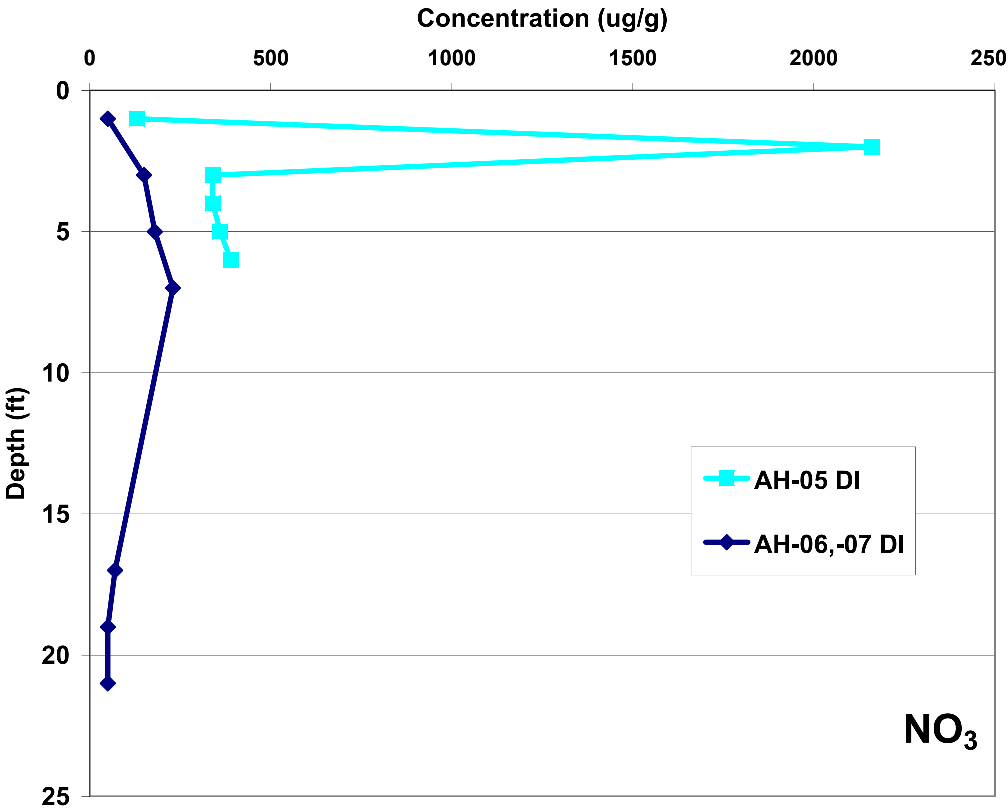
100
200
300
400
500
600
700
800
900
Depth (ft)
0
5
10
15
20
25
AH-05 DI
AH-06,07 DI
Cl


Concentration (ug/g)
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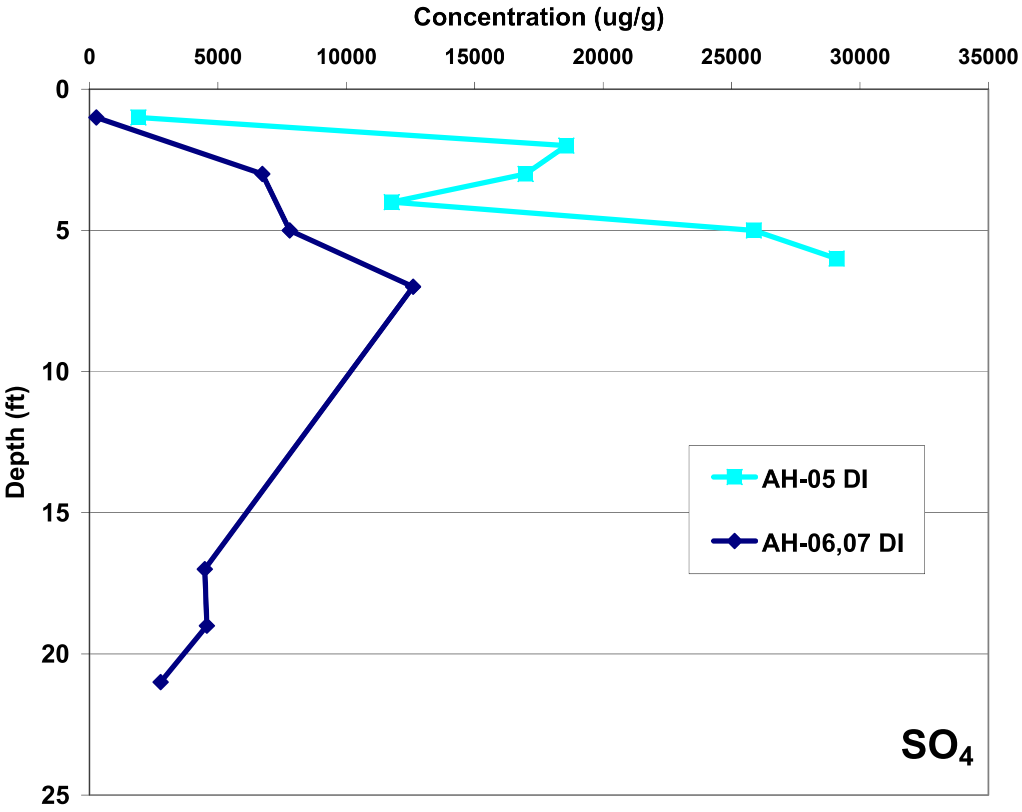
500
1000
1500
2000
2500
Depth (ft)
0
5
10
15
20
25
AH-05 DI
AH-06,-07 DI
NO_3


Concentration (ug/g)
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5000
10000
15000
20000
25000
30000
35000
Depth (ft)
0
5
10
15
20
25
AH-05 DI
AH-06,07 DI
SO_4