Department of Energy
Washington, DC 20585

November 21, 2014

U.S. Nuclear Regulatory Commission
Attn: Document Control Desk
Deputy Director
Mail Stop T8F5
Washington, DC 20555-0001

Subject: *Site Status Report: Groundwater Flow and Contaminant Transport in the Vicinity of the Bluewater, New Mexico, Disposal Site*

To Whom It May Concern:

The purpose of this letter is to transmit for U.S. Nuclear Regulatory Commission (NRC) staff review the enclosed Site Status Report for the Bluewater, New Mexico, Uranium Mill Tailings Radiation Control Act (UMTRCA) Title II Disposal Site.

In 2010, the uranium concentration in an alluvial aquifer point-of-compliance (POC) well at the Bluewater site exceeded the approved alternate concentration limit stipulated in the site's Long-Term Surveillance Plan (LTSP). After installation of additional monitoring wells in 2011 and 2012, and initial evaluations of sample results obtained from the new wells, the U.S. Department of Energy, Office of Legacy Management (DOE-LM) determined that contaminated groundwater in both the alluvial and San Andres aquifers was leaving the site. DOE-LM prepared an evaluative monitoring work plan for NRC review, as required by the LTSP, to address issues associated with elevated uranium concentrations in the site aquifers.

In a letter from NRC to DOE-LM dated January 24, 2013 (*NRC Comments on DOE's June 27, 2012, Letter Regarding Evaluative Monitoring Work Plan for the Bluewater, New Mexico Disposal Site*), NRC requested DOE-LM to conduct the following evaluations.

1. Determine the extent of the plume leaving the site.
2. Evaluate disposal cell cover performance.
3. Conduct a risk assessment to evaluate the risk to the public from the contaminants leaving the site.

Follow-on discussions with the NRC clarified that a qualitative assessment of risk to the public with available information was sufficient to address the third evaluation, with the purpose of evaluating imminent risk.

The referenced Site Status Report addresses the evaluations requested by NRC. An exhaustive search was conducted to obtain and evaluate available documentation prepared by the former licensee and its hydrology subcontractors, geologic maps, and hydrogeologic reports pertaining to the Bluewater site and the Grants-Bluewater Valley site, groundwater data collected by the former licensee and DOE-LM, and historical and current groundwater, and surface water data collected by various public and private entities in the Grants-Bluewater Valley.

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DOE-LM evaluated the hydrogeology and groundwater chemistry within a 195-square-mile study area that encompasses the Bluewater site, groundwater recharge and discharge areas associated with the site aquifers and public and private groundwater users that potentially could be affected by Bluewater site-related contamination. Of particular concern were the municipal water supply systems for the nearest communities of Bluewater, Milan, and Grants, New Mexico.

The primary observations derived from this investigation are summarized according to NRC's requested evaluations.

Determine the extent of the plume leaving the site

- The site aquifers were contaminated during milling operations. Seepage from the tailings impoundments entered the alluvial and San Andres aquifers and formed a mineralized zone in the geologic materials under the impoundments. The mineralized zone constitutes a continuous source of contamination for both aquifers.
- Contaminated Rio San Jose alluvial groundwater flows southeast from the Bluewater site and merges with contaminated San Mateo Creek alluvial groundwater that flows west from the Homestake site. The merged area is about 1 mile southeast of the Bluewater site. The combined aquifer flows in the southeast direction toward Milan. The proportional contribution of the groundwater flow and contaminant mass from the Bluewater site has not been determined.
- Contaminated San Andres aquifer groundwater flows in the east-southeast direction toward the Homestake site. The flow path for the aquifer is well north of the Milan water supply wells and continues to areas north of Grants.
- Uranium concentrations decrease with distance from the Bluewater disposal cell in both aquifers. Dispersion is the primary mechanism for uranium attenuation.
- Uranium concentrations exceeding the drinking water standard are present in the combined alluvial groundwater as least as far as Toltec, which is upgradient of Milan. The uranium plume appears to be shrinking because of aquifer remediation being conducted by Homestake Mining Company.
- The leading edge of the uranium plume in the San Andres aquifer appears to be a short distance downgradient of the Homestake site. Bluewater-derived uranium contamination reached the Homestake site as early as 1980 and has been essentially stable since that time.

Evaluate disposal cell cover performance

- Although leakage from the main tailings disposal cell is likely still occurring, the rate of seepage and contaminant mass is insignificant compared to the seepage and contamination that occurred during milling.

- Shallow depressions and precipitation that ponds in them do not have a detrimental effect on the performance of the disposal cell cover. The depressions formed due to continued consolidation of slimes contained in the north portion of the cell. Most of the ponded water evaporates because of the regional climatic conditions and because a very thick layer of clay material underlying the affected portion of the cover limits infiltration. Also, radon flux measurements verified that the radon barrier has not been damaged by the deformation of the cell cover and, therefore, is performing as designed.
- Elevated uranium concentrations in the alluvial POC well are not indicative of a surge of fluids from the disposal cell. They are attributed to decreasing water levels in the aquifer at the well location (the well is currently dry).

Conduct a risk assessment to evaluate the risk to the public from the contaminants leaving the site

- No known alluvial wells in the vicinity of the Bluewater site that are used for drinking water purposes have uranium concentrations above the drinking water standard.
- No known drinking water wells are currently completed in the estimated San Andres aquifer uranium plume.
- The direction of groundwater flow in the San Andres aquifer, the apparent stability of the uranium plume in the aquifer, and the locations of municipal supply wells indicate that Bluewater site-derived uranium contamination does not present an imminent or foreseeable risk to community water systems in the Grants-Bluewater Valley.

The evaluations and conclusions provided in the Site Status Report address NRC's requests listed above. DOE-LM will continue to monitor the aquifers through sampling of the site wells and evaluation of the data, but proposes that additional disposal cell and groundwater investigations are unnecessary.

DOE-LM proposes to revise the LTSP to reflect the conclusions in the Site Status Report by making the following monitoring changes (a map of the current well network is enclosed for reference). The revised LTSP would be submitted to NRC for review and acceptance.

1. Revise tables and maps to add the 10 new wells to the original 9 wells in the site monitoring network.
2. Change the alluvial aquifer POC location to well 22(M) because POC well T(M) is currently dry.
3. Change the alluvial aquifer point-of-exposure (POE) location to well 21(M) because of the inconsistency of available water in POE well X(M).
4. Change the San Andres aquifer POC location to well 16(SG) because of the poor condition of POC wells OBS-3 and S(SG).
5. Decommission wells OBS-3 and S(SG).
6. Sample the monitoring well network annually for 5 years and then once every 3 years if there are no significant upward trends. Major ions will be included in the analyte suite.

In summary, DOE-LM has determined that there is no imminent threat to human health and the environment, and that site conditions do not meet the "DOE Criteria for Maintenance and Emergency Measures" as described in Table 3-2 of the LTSP. As such, DOE-LM has no legal authority under UMTRCA to perform actions other than ongoing monitoring of the plume to ensure that protection of human health and environment objectives continue to be met.

Please call me at (970) 248-6550 if you have any questions. Please send any correspondence to:

U.S. Department of Energy
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Sincerely,

Deborah L. Barr 11/20/14

Deborah L. Barr
Site Manager

Enclosures

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File: BLU 410.02 (rc grand junction)

LMS/BLU/S11381

Site Status Report: Groundwater Flow and Contaminant Transport in the Vicinity of the Bluewater, New Mexico, Disposal Site

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Plates

Abbreviations

ACLs	alternate concentration limits
amsl	above mean sea level
Anaconda	Anaconda Copper Company
AR	uranium activity ratio
ARCO	Atlantic Richfield Company
bgs	below ground surface
cfs	cubic feet per second
cm/s	centimeters per second
DO	dissolved oxygen
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ft	foot or feet
ft^2	square feet
ft^3	cubic feet
ft/day	feet per day
ft^2/day	square feet per day
ft/yr	feet per year
gpm	gallons per minute
GRP	Grants Reclamation Project
HMC	Homestake Mining Company
Ks	saturated hydraulic conductivity
LiDAR	light detection and ranging
LTSP	Long-Term Surveillance Plan
MCL	maximum concentration limit
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter
mi	mile or miles
mg/L	milligrams per liter
NMED	New Mexico Environment Department
NRC	U.S. Nuclear Regulatory Commission
pCi/L	picocuries per liter
pCi/m^2s	picocuries per square meter per second

redox	oxidation-reduction
SRNL	Savanah River National Laboratory
TDS	total dissolved solids
U-234	uranium-234
U-238	uranium-238
UMTRCA	Uranium Mill Tailings Radiation Control Act
USGS	U.S. Geological Survey

Executive Summary

This site status report presents an assessment of the groundwater systems impacted by the Bluewater, New Mexico, Disposal Site (Bluewater site; the site), a former uranium milling facility in Cibola County, New Mexico. The Anaconda Copper Company (Anaconda) and Atlantic Richfield Company (ARCO) processed uranium ore at the site from 1953 to 1982. Onsite areas impacted by the mill were reclaimed in following years, and the site was transferred to the U.S. Department of Energy (DOE) in 1997 for long-term surveillance and maintenance.

The DOE Office of Legacy Management manages the facility and is responsible for monitoring groundwater quality at the site. Monitoring results indicate that the upper two aquifers at the site are contaminated with mill-related constituents and that groundwater containing elevated concentrations of uranium is migrating beyond the site boundary. This is a serious concern because water is withdrawn from these aquifers downgradient of the site for drinking water, irrigation of agricultural land, and various industrial uses.

The primary objective of this study was to develop a groundwater conceptual model that describes the aquifers associated with the Bluewater site and the potential exposure of downgradient groundwater users to mill-related contamination. A study area encompassing approximately 195 square miles incorporates the contaminant source areas, the hydrologic and hydrogeologic features that most directly influence groundwater flow and contaminant transport in the Grants-Bluewater Valley, and the points of use, particularly the downgradient communities of Milan and Grants.

This study has found that numerous hydrogeologic processes affect contaminant transport in the region. The complex nature of these processes and the limited data to fully characterize them makes it challenging to accurately delineate the extent of subsurface milling-related contamination at the Bluewater site. This report includes a summary of uncertainties that impact the understanding of contaminant migration and fate in the region, and their significance regarding the conclusions drawn for the conceptual model. Despite the uncertainties, certain conclusions, including those summarized below, can be drawn from the evaluation of existing data. These conclusions are organized into the following three topics: sources of contamination, groundwater flow and transport, and potential risks to groundwater users.

Sources of Contamination

- The Anaconda/ARCO Bluewater uranium milling operations contaminated the aquifer in the ancestral Rio San Jose alluvial system and also contaminated the deeper bedrock San Andres aquifer in the San Andres Limestone and Glorieta Sandstone formations. Seepage of tailings fluid from the mill's tailings impoundments not only entered the two aquifers but apparently created a mineralized zone in the geologic strata (basalt, alluvium, limestone, and sandstone) and fault zones under the impoundments.
- Several billion gallons of tailings fluid (leachate) seeped through the bottom of the Bluewater main tailings impoundment and into the underlying aquifers prior to construction of the disposal cell cover in 1995. Estimated hydraulic properties of the cell cover and the tailings materials suggest that tailings fluids may continue to seep from the disposal cell indefinitely. However, the volume of fluid and mass of contaminants seeping from the cell

since it was constructed are very small compared to the volume and mass that seeped through the bottom of the tailings impoundment during milling operations.

- Uranium is mobilized in the alluvial and San Andres aquifers primarily by release of solid-phase uranium in the mineralized zone beneath the Bluewater site's main tailings disposal cell to groundwater flowing beneath the cell.
- The uranium release mechanisms in the subsurface at the site constitute a continuous contaminant source that produces uranium concentrations in onsite monitoring wells that are effectively constant or decreasing very slowly. It is assumed that this contaminant source will remain indefinitely.
- Operations at the Homestake uranium mill, located several miles southeast of the Bluewater site, contaminated the San Mateo Creek alluvial aquifer underlying the Homestake tailings piles. This is the primary source of contaminated alluvial groundwater in the vicinity of Milan.

Groundwater Flow and Transport

- Groundwater in the Rio San Jose alluvium flows southeast from the Bluewater site and merges with San Mateo Creek alluvial groundwater. The combined flow, which contains contaminants from both the Bluewater and Homestake sites, continues southeast toward Milan.
- Flow paths for the groundwater migrating from the Bluewater site in the San Andres aquifer are in the east-southeast direction from the site and, consequently, do not intersect municipal wells for the communities of Bluewater and Milan. Groundwater flow paths from the site appear to head toward areas north of Grants.
- The geology of the San Andres Limestone and Glorieta Sandstone provides an environment for a highly productive aquifer. Wells completed in karst features in the upper portion of the San Andres Limestone have high production rates with minimal drawdown. Fault, fracture, and solution channel and cavity features within both formations enhance the productivity of the aquifer and serve as conduits for high groundwater flow rates. Groundwater flows at much lower rates through the unfractured sandstone units within the aquifer.
- Groundwater flowing beneath and downgradient of the site in both the alluvial and San Andres aquifers is in an oxidized state. Consequently, dissolved uranium migrates with the groundwater flow instead of precipitating out of solution. Groundwater flow paths and uranium transport are correlated.
- Uranium concentrations in both aquifers decrease in transport distance from the Bluewater site, indicating that natural contaminant attenuation processes are active in the aquifers.
- The volume of flow and contaminant mass contributed by San Mateo Creek alluvial groundwater to the Milan area appear to be much greater than those contributed by Rio San Jose alluvial groundwater. The actual proportion of Bluewater-derived uranium in the alluvial aquifer downgradient from where flows from the respective sources merge is unknown.
- Evaluation of historical and current uranium concentrations in groundwater suggests that the uranium plume in the alluvial aquifer is shrinking, primarily due to remediation at the Homestake site. The uranium plume in the San Andres aquifer has been stable since the

early 1980s, such that uranium concentrations above the regional background concentration are essentially constant.

Potential Risk to Groundwater Users

- DOE sampled several private wells near the Bluewater site, completed in the alluvial and San Andres aquifers, in 2012 and 2013. The closest alluvial well to the site, although not used for drinking water, has uranium concentrations well below the drinking water standard. A groundwater sample from the closest San Andres aquifer well, which is not permitted or used for drinking water, had a uranium concentration higher than the drinking water standard. None of the private drinking water supply wells that DOE sampled in the vicinity of the Bluewater site have uranium concentrations exceeding the drinking water standard.
- Available groundwater data suggest that Bluewater-derived contamination does not adversely affect any private wells used for drinking water. However, not all of the well owners near the site allowed DOE to sample their wells. Although the unsampled wells do not appear to be within the groundwater flow paths emanating from the Bluewater site, it cannot be stated with certainty that groundwater in all private drinking water wells in the vicinity of the Bluewater site have uranium concentrations below the drinking water standard.
- The municipal water supply wells for Bluewater, Milan, and Grants pump water from the San Andres aquifer. Reported concentrations of dissolved uranium for those wells have all been less than the New Mexico drinking water standard and do not show an upward trend in uranium concentrations.
- Collectively, the direction of groundwater flow in the San Andres aquifer, the apparent stability of the uranium plume in the aquifer, and the locations of municipal supply wells indicate that Bluewater site–derived uranium contamination does not pose a current or future risk for community water systems in the Grants-Bluewater Valley.

Conclusions drawn from this conceptual model can only be confirmed through continued groundwater monitoring and evaluation of groundwater data. Existing and future activities involving Bluewater site–related contamination must continue to focus on protection of public health and the environment. This conceptual model is considered to be an important tool for use by DOE and other public entities to accomplish this goal.

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1.0 Introduction and Objectives

1.1 Introduction

The Bluewater, New Mexico, Disposal Site (the Bluewater site; the site) is a former uranium milling facility in Cibola County in the northwest region of New Mexico (Figure 1). The Anaconda Copper Company (Anaconda) and Atlantic Richfield Company (ARCO) processed uranium ore at the site from 1953 to 1982. Milling operations contaminated the upper two aquifers at the Bluewater site. The U.S. Department of Energy (DOE) Office of Legacy Management (LM) currently manages the site and its responsibilities include monitoring the contaminated aquifers.

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Figure 1. Regional Location Map

Groundwater in the region is used for several purposes. Alluvial groundwater is used primarily as drinking and livestock water by residences that are not connected to municipal water supply systems. The primary water supply source in the region is a bedrock aquifer, which is used by the communities of Bluewater, Milan, and Grants and is used for local industrial and agricultural purposes.

Because of the importance of groundwater in the region, DOE is evaluating impacts to human health and the environment from groundwater contamination associated with the mill operations. To help meet this objective, this report includes a conceptual model of contaminant transport processes in the aquifers impacted by the Bluewater site.

1.2 Groundwater Issues

Processing of uranium ore at the Bluewater mill produced radioactive tailings, which were stored onsite at two locations referred to as the carbonate tailings pile and the main tailings impoundment. As early as the late 1950s, the tailings had been identified as sources of contamination for two aquifers beneath the mill property. Some of the contamination impacted an alluvial aquifer that occurs in river sediments of the ancestral Rio San Jose that were covered by a succession of basalt lava flows. Significant contamination was detected in two bedrock formations at the site—the San Andres Limestone and the Glorieta Sandstone. These formations together act as a single, prolific regional source of groundwater referred to in this report as the San Andres aquifer. As discussed in Chapter 6, Anaconda and ARCO took multiple steps to reduce the capacity of the main tailings impoundment to be a source of contamination in the alluvial and San Andres aquifers.

During early milling operations, nitrate was identified as a site-related contaminant that impacted the alluvial and San Andres aquifers. In following years, the metals molybdenum, selenium, and uranium became the main constituents of concern stemming from the leaching of tailings. Additionally, studies of the Bluewater site in the late 1970s and early 1980s suggested that locally elevated concentrations of dissolved chloride and sulfate indicated mill-related contamination.

Accordingly, water chemistry parameters reflective of total salinity, such as total dissolved solids (TDS) concentration, have been used to help delineate the spatial extent of conservative (i.e., nonretarded) constituents in groundwater. Measured concentrations of chloride, sulfate, and TDS in the regional groundwater are generally not high enough to be significant threats to human health and the environment. In contrast, uranium is a contaminant that potentially poses a risk to drinking water users, and it is mobile and widespread in regional groundwater. For this reason, much of this study focuses on the assessment of uranium concentrations in the alluvial and San Andres aquifers and on physicochemical processes that affect subsurface uranium transport.

Dissolved uranium in the alluvial and San Andres aquifers is of particular interest in this assessment because of another significant source of uranium contamination in the Grants-Bluewater Valley. The Homestake site, a former uranium mill, is about 3.5 miles (mi) east-southeast of the Bluewater site. Homestake Mining Company (HMC) owns the facility, which processed ore from 1958 to 1990. Today the Homestake property and surrounding areas are also referred to as the Grants Reclamation Project (GRP), as the company's focus is on site reclamation and remediation of the underlying alluvial aquifer. The alluvial aquifer at the

Homestake site has been contaminated by HMC mill operations and by former uranium mining and milling operations in upgradient parts of the San Mateo Creek drainage basin. Groundwater in this alluvial aquifer not only flows southwest from the Homestake site toward Milan, but also to the west, where it merges with Rio San Jose alluvial groundwater coming from the Bluewater site.

In addition to uranium, much of the contamination in the San Mateo Creek alluvium at the Homestake site consists of dissolved selenium. According to HMC, none of the contamination generated by the milling has migrated as deep as the San Andres aquifer beneath the facility, primarily because a thick section of the low-permeability Chinle Formation acts locally as an effective aquitard between the alluvial and San Andres aquifers. Extensive subsurface remediation operations at the Homestake site complicate flow and transport processes in a groundwater system that is complex even under natural flow conditions.

Milan and Grants are hydraulically downgradient of the Bluewater and Homestake sites (Figure 2). The two municipalities withdraw groundwater from the San Andres aquifer for drinking water using multiple pumping wells located from about 2.5 to 7 mi from the Bluewater site. Given their respective locations relative to the former mill sites, both Milan and Grants monitor dissolved uranium in their municipal wells to verify that levels remain below the State of New Mexico maximum concentration limit (MCL) for the constituent, which is 0.03 milligram per liter (mg/L). Publicly available water chemistry data for all of the Milan and Grants municipal wells indicate that uranium concentrations are below the MCL. This observation also holds true for a single community well tapping the San Andres aquifer that is used to supply drinking water to the Village of Bluewater, about 1.5 mi west-southwest of the Bluewater site.

1.3 Objectives

The primary objective of this study is to develop a groundwater conceptual model that describes the extent of contamination associated with the Bluewater site and the potential risk to downgradient groundwater users. Developing the model of the groundwater system requires an understanding of milling history, site and regional geology, site and regional hydrogeology and groundwater chemistry, disposal cell performance, and groundwater contamination and uranium transport.

The scope of work necessary to develop the conceptual model includes addressing the following specific objectives.

- Identify the sources of groundwater contamination at the site and within the study area, addressing the contributions of contaminants from the Bluewater and Homestake mill sites.
- Describe the geology of the study area, identifying geologic features that affect the groundwater systems.
- Evaluate site and regional hydrology and hydrogeology to determine the sources of groundwater and how groundwater flows through the study area.
- Describe the ambient chemistry of water resources in the study area, including the water quality of surface water resources and chemistry of groundwater in the alluvial and San Andres aquifers and the interlying Chinle Formation.

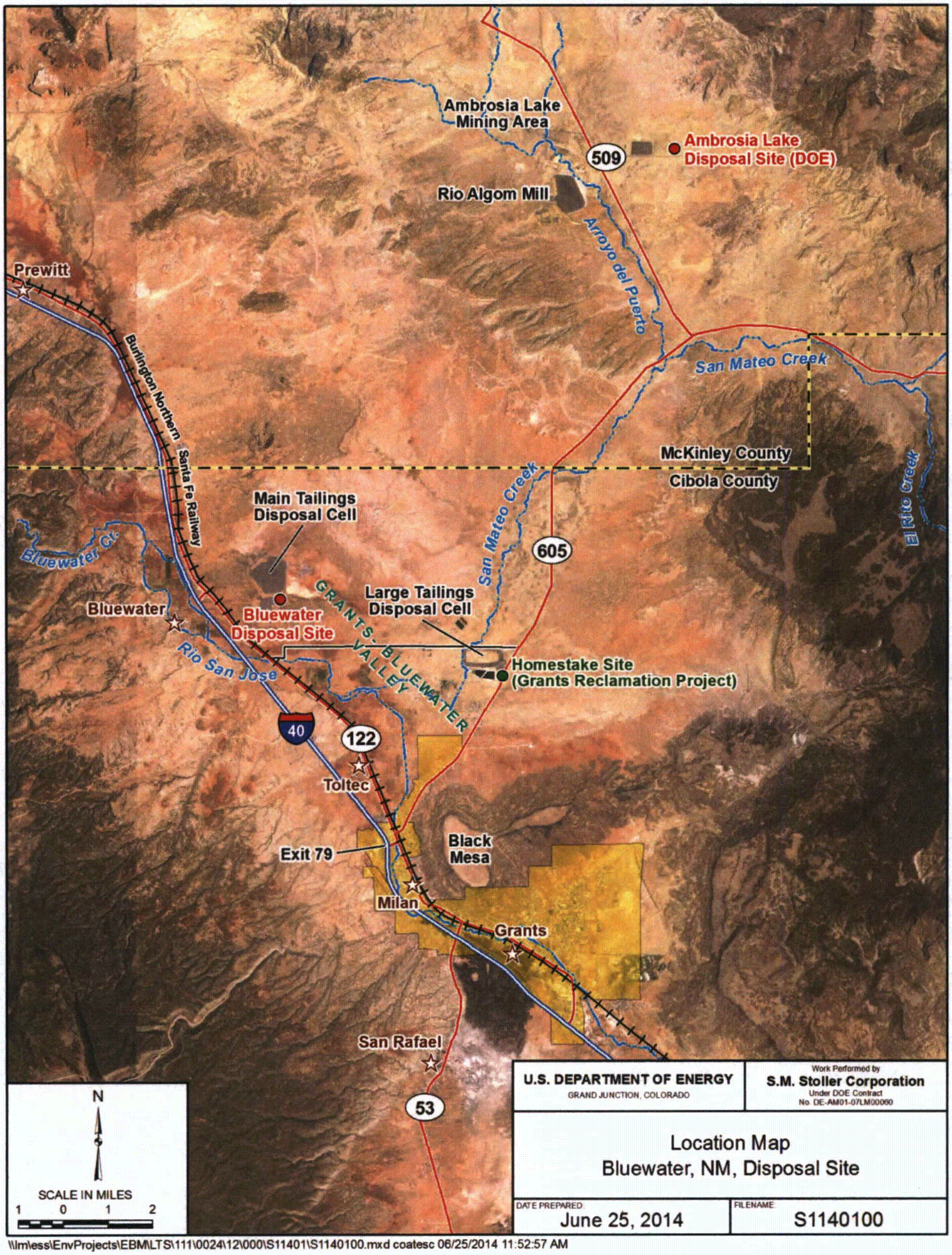

Figure 2. Location Map for the Bluewater Disposal Site

- Evaluate the performance of the main tailings disposal cell to determine if it is a continuing source of contamination to the local aquifers.
- Describe the most likely mechanisms for mobilizing uranium and other dissolved constituents in the aquifers.
- Describe the history of uranium contamination originating at the Bluewater site and its spatial distribution within the site and the region.
- Develop a comprehensive assessment of physicochemical phenomena that likely influence contaminant transport in the regional and site groundwater systems.
- Assess the potential fate of uranium and other contaminants in the study area.
- Evaluate the potential risk of site-related contamination impacting regional groundwater users, particularly the municipal water supplies for Bluewater, Milan, and Grants.
- Describe uncertainties associated with components of the conceptual model and how they affect the model's conclusions.

Geologic reports, groundwater investigations conducted at both site and regional scales, and data collected by DOE were used to develop the conceptual model. Appendix D presents summaries of reports from previous studies pertinent to development of the conceptual model.

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2.0 Study Area

The Bluewater site is in Cibola County, about 9 mi northwest of Grants, the county seat. The Grants-Bluewater Valley, which contains the site and the communities of Bluewater, Milan, and Grants, lies within the Acoma-Zuni section of the southeast part of the Colorado Plateau physiographic province. The climate of this part of New Mexico is semiarid to arid, with a mean annual precipitation at Grants of about 10 inches. Precipitation generally increases with altitude in the region.

A transportation corridor comprising Interstate 40, State Highway 122, and the Burlington Northern Santa Fe Railway traverses the region in a southeast-northwest direction (Figure 2). State Highway 605, starting at Milan, is in the San Mateo Creek valley and passes by the Homestake site. From its intersection with Interstate 40 on the northwest end of Grants, State Highway 53 heads south toward San Rafael (Figure 2).

2.1 Study Area Description

Given the relatively high mobility of contaminants like uranium, the regional presence of community water systems dependent on groundwater in the San Andres aquifer, and the presence of another contaminant source due to milling, DOE has developed a conceptual model that accounts for hydrogeologic processes over a much larger geographic area than the Bluewater site itself. In addition to incorporating parts of the regional groundwater flow system hydraulically downgradient of the former Bluewater mill, the model also includes areas upgradient of the site that contribute recharge to, and therefore constitute sources of, groundwater flowing beneath the Bluewater site. The regional approach to assessing flow and transport processes is considered crucial to fully address potential risks to offsite users of groundwater in the alluvial and San Andres aquifers.

The geographic region of the conceptual model is a rectangular area about 13 mi east to west and 15 mi north to south (Figure 3). The north boundary of the study area roughly coincides with the Cibola County border with McKinley County, and the south boundary is about 4 mi south of Grants. The area's west boundary is about 5 mi west of the Bluewater site, and the east boundary captures the Homestake site and the east portion of Grants. With a total area of about 195 square mi, the study area completely covers four townships and a portion of each of five additional townships. Previous geologic mapping and hydrogeologic investigations encompass this study area and were used extensively in the preparation of this report.

Figure 3 and Plate 1 show a topographic map of the study area assembled from U.S. Geological Survey (USGS) quadrangles. Significant topographic features in the study area include Black Mesa, northwest of Grants, and the Zuni Mountains on the southwest side of the Grants-Bluewater Valley. The highest point in the study area (approximately 9,000 feet [ft] above mean sea level [amsl]) is in the Zuni Mountains. The basalt-covered Black Mesa has an elevation of about 7,200 ft amsl. A basalt-covered area (Bluewater Basalt) is also found to the west, south, and southeast of the Bluewater site, within a broad fluvial valley cut by the ancestral Rio San Jose. Major basalt flows (Zuni Canyon Basalt and El Calderon Basalt) are also seen at ground surface in areas south of Grants (Figure 3). The Homestake site is distinguished by the footprint of the large tailings disposal cell.

Principal land uses in the study area include agriculture in the form of irrigated farming and cattle ranches, small business along the Interstate 40 corridor, and industrial land use in Milan and Grants. Residential land use occurs in Milan, Grants, Bluewater, San Rafael, at five subdivisions south of the Homestake site, and at scattered single residences. The economy of the area is based on ranching, alfalfa and hay production, and tourism. Land ownership in the region is varied. In addition to privately owned property, the federal, state, county, and municipal governments own land, and portions of the Grants-Bluewater Valley and the Zuni Mountains contain Native American land.

Bluewater Creek, which emerges from Bluewater Canyon at the foot of the Zuni Mountains and joins with Mitchell Draw in the northwest corner of the study area (Figure 3) to form the present Rio San Jose, is significant because it is the only stream in the area that maintains flow in most years. Under historical natural conditions, the creek was perennial to the mouth of Bluewater Canyon. Since 1927, however, flow in the creek has been regulated where it empties out of Bluewater Lake, which is about 5 mi west of the study area's west boundary. Bluewater Lake and Bluewater Creek are major sources of recharge to groundwater that flows beneath the Bluewater site. A major surface water diversion structure on Bluewater Creek, about 0.5 mi south of the mouth of Bluewater Canyon (Figure 3), routes water to canals delivering irrigation water to land in the Grants-Bluewater Valley.

2.2 Bluewater Site History

Anaconda constructed the uranium mill at the Bluewater site in 1953 and began processing ore the same year. The U.S. Atomic Energy Commission was the first regulator of operations at the Bluewater mill. The State of New Mexico later assumed regulatory authority for the site in accordance with provisions in the Atomic Energy Act of 1954. The U.S. Nuclear Regulatory Commission (NRC) became the site regulator in 1986 after the State relinquished its regulatory responsibilities.

No uranium mining occurred on the Bluewater site or within the study area. The effects that uranium mining and milling activities in the San Mateo Creek basin have had on groundwater hydrology in the study area are addressed in subsequent chapters of this report.

2.2.1 Milling

ARCO purchased Anaconda in 1977, and the Anaconda Bluewater mill became known as the ARCO Bluewater mill in the early 1980s. The site was licensed under provisions of the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). The Bluewater mill was considered an UMTRCA Title II site, which applies to uranium mill sites that were active at the time the act was passed. Title II of the legislation required that, upon completion of remediation at a site, either the federal government or the state in which a mill was located would assume long-term custodial responsibilities.

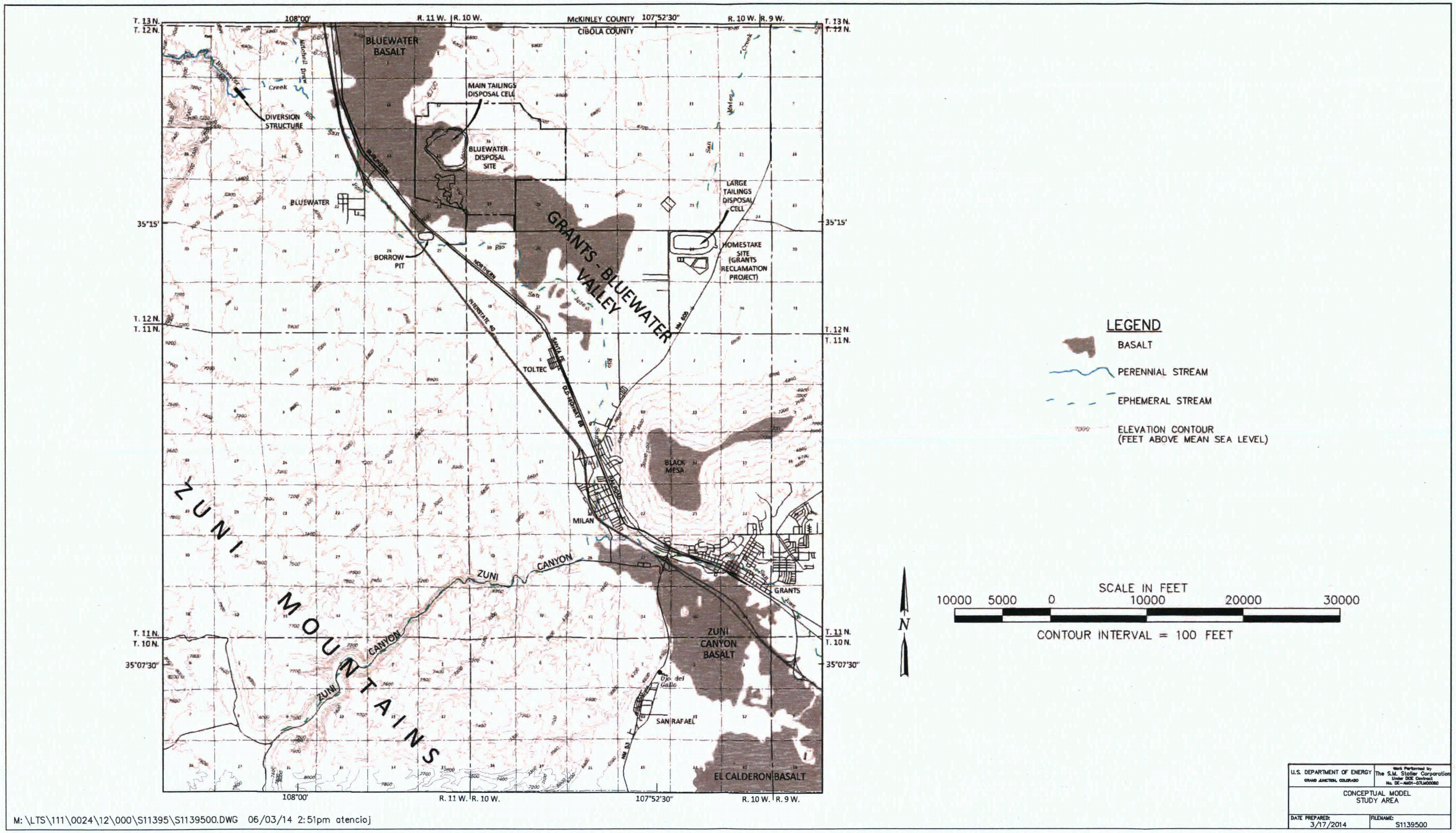

Figure 3. Conceptual Model Study Area

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The Bluewater mill initially used a carbonate-leach process to extract uranium from ore mined from nearby mines in the Todilto Limestone, processing 300 tons of ore per day. Tailings produced from the carbonate process were disposed of in natural depressions in the Bluewater Basalt adjacent to the mill; these tailings were eventually encapsulated within the carbonate tailings cell (Figure 4). An acid-leach process replaced the carbonate-leach process in 1955 after discovery of sandstone uranium ores and development of mines on the Laguna Reservation east of Grants. The ore-processing rate eventually reached 6,000 tons per day.

Tailings from the acid-leach process were placed in a natural basin north of the carbonate tailings that became the main tailings impoundment. Heavier, coarse sand material settled near the south end of the impoundment, and finer materials settled in the north end. Chapter 6 discusses the spatial distribution of tailings materials in the main tailings impoundment. The last year of uranium ore milling at the site was 1982; mill operations to recover uranium from leachate fluids continued for several more years. Upon completion of site reclamation in 1995, the encapsulated tailings piles became known as the carbonate and main tailings disposal cells.

To reduce the amount of tailings fluids seeping from the main tailings impoundment into the underlying aquifers, Anaconda began disposing of fluids in a deep injection well located about a mile northeast of the impoundment (shown as the Anaconda injection well in Figure 4). This well was used between 1960 and 1977. Beginning in 1977, the tailings fluids were pumped to lined evaporation ponds north and northeast of the impoundment (Figure 4). These disposal processes are described further in Chapter 6 and Appendix A.

2.2.2 Site Decommissioning

ARCO submitted a decommissioning plan for the Bluewater mill to NRC in 1987. Upon NRC's approval of the plan in 1989, ARCO began demolition of buildings on the facility as well as residences in an Anaconda housing area south of the mill. The decommissioning process and site reclamation, including stabilizing the two tailings piles in place as engineered disposal cells and remediating the evaporation ponds, was completed in 1995.

During site reclamation activities, the tailings and other contaminated materials were encapsulated in six onsite disposal areas: the main tailings disposal cell (354 acres), the carbonate tailings disposal cell (54 acres), Disposal Area No. 1 (11 acres) containing mill debris, a small cell containing radiologically contaminated polychlorinated biphenyl materials within Disposal Area No. 1, another small cell containing radiologically contaminated asbestos materials, and two small landfills (totaling 2 acres) containing miscellaneous waste and milling byproduct material (ARCO 1996). All of these disposal areas contain potential groundwater contamination sources. Additionally, about 210 acres of undisturbed basalt surfaces containing contaminated windblown materials were not remediated because of the rough surfaces (ARCO 1996, DOE 1997); the affected areas are also potential contamination sources.

Site reclamation included an unsuccessful attempt to remediate the aquifers. ARCO abandoned and plugged the deep injection well in late 1995 in accordance with requirements of the New Mexico Office of the State Engineer and the New Mexico Water Quality Control Commission.

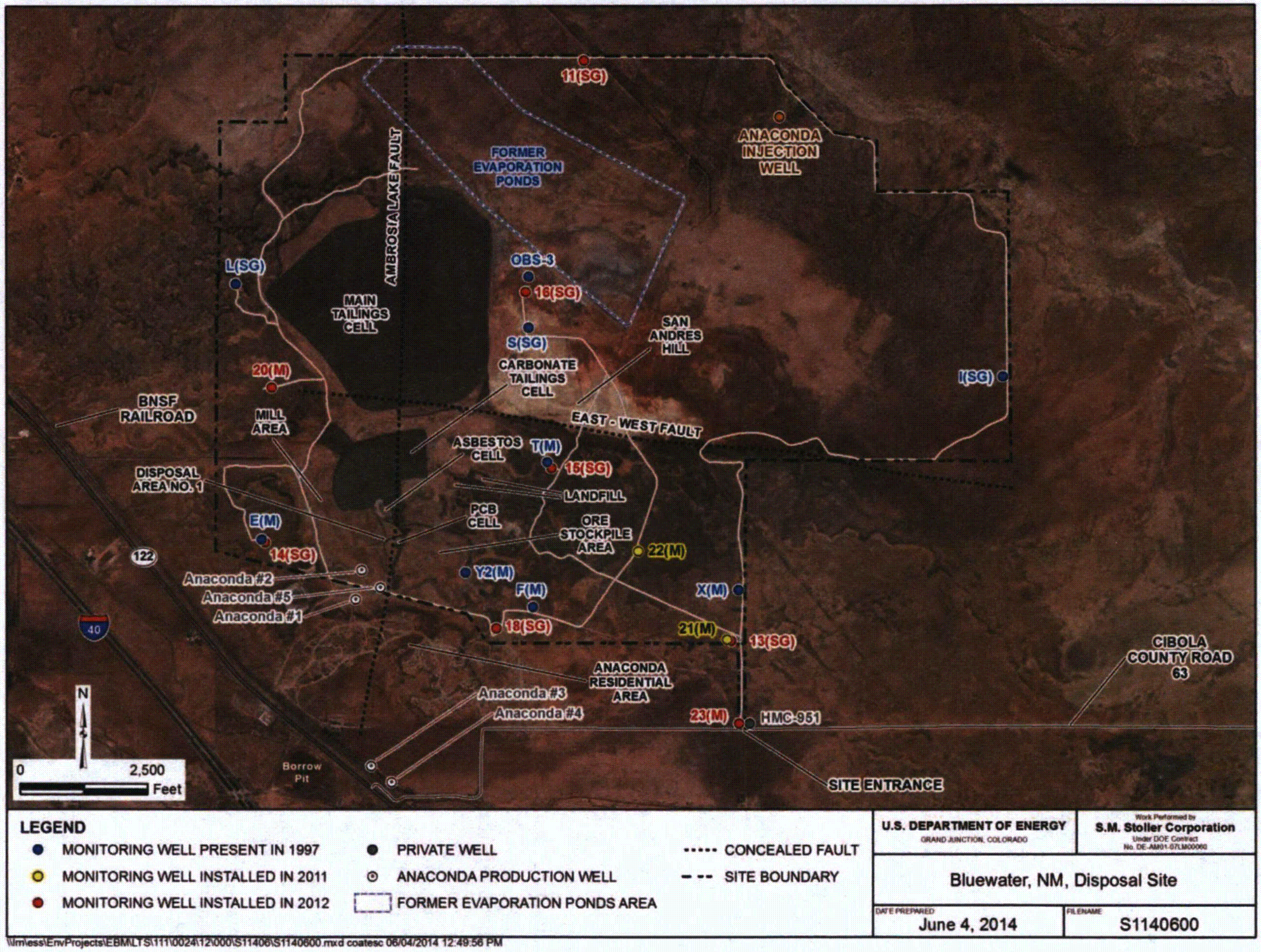

Figure 4. Bluewater Site and Surrounding Area

DOE assumed responsibility for the Bluewater mill site in 1997 after the State of New Mexico declined to take over long-term management duties. DOE manages the site in accordance with an NRC-approved Long-Term Surveillance Plan (LTSP) to ensure protection of human health and the environment. Requirements of the LTSP (DOE 1997) include ensuring that reclaimed features at the facility (disposal cells and landfills) function as designed and that onsite groundwater chemistry meets approved water quality standards.

2.2.3 Historical Site Groundwater Issues

Anaconda became aware as early as the late 1950s that contaminated mill process water from the main tailings impoundment was impacting the alluvial and San Andres aquifers (West 1972). This observation was supported further in consulting reports produced in the late 1970s by Hydro-Search (1977, 1981a), and again in the early- to mid-1980s in reports by Dames & Moore (1986a, 1986b).

Downward seepage of liquids from sandy and clay-rich tailings in the main tailings impoundment to underlying geologic units was considered to be the source of the contamination in the aquifers beneath and near the impoundment. ARCO estimated that approximately 5.7 billion gallons of tailings fluids seeped from the main tailings impoundment prior to encapsulation in 1995, with about 2.7 billion gallons occurring prior to 1960 when deep-well injection began. These seepage estimates are described in greater detail in Chapter 6 and Appendix A.

Contaminated groundwater in the alluvial aquifer resulted from downward seepage from both tailings piles through underlying porous basalt and into the buried sand and gravel deposits of the ancestral Rio San Jose. The contaminated alluvial groundwater was then transported southeastward, mostly within the Rio San Jose paleodeposits.

Downward-seeping contaminants from the main tailings impoundment also entered the San Andres aquifer, particularly where the base of the southeast portion of the impoundment directly contacts the San Andres Limestone. Additionally, some of the contamination in the San Andres aquifer was caused by tailings liquids that first migrated through a thin layer of basalt in direct contact with the tailings, and then to limestone and sandstone in the bedrock. It is also possible that some tailings leachate feeding ancestral Rio San Jose alluvium south of the impoundment subsequently migrated northeastward into the San Andres aquifer east of the main tailings impoundment.

The role that faults in the vicinity of the tailings played in affecting groundwater flow and contaminant transport during and shortly after milling years was not fully understood at the time. A north-striking fault (Ambrosia Lake Fault), which bisects the bedrock formations under the main tailings impoundment, is known to intersect an east-striking fault (East-West Fault) under the south side of the main tailings impoundment. Though both features may represent partial barriers to San Andres aquifer groundwater flow, each also likely acts as a conduit, helping to convey groundwater vertically from alluvium to the San Andres aquifer as well as horizontally along the fault zone.

During the milling period, some contamination was detected in the San Andres aquifer as far as 0.75 mi directly south of the main tailings impoundment (i.e., south of the East-West Fault). In particular, uranium and nitrate concentrations above background levels were detected in Anaconda #2 water-supply well used by Anaconda for milling. Anaconda pumped this well and other San Andres aquifer production wells south of the mill (Anaconda #1, #3, #4, and #5 shown in Figure 4), creating a cone of depression that had the potential to induce southward flow of groundwater in the San Andres aquifer. It appears likely that the Ambrosia Lake Fault provided a conduit for the southward transport of contaminants from seepage from the main tailings impoundment. However, ARCO did not consider contamination in the San Andres aquifer south of the East-West Fault to be of concern because a downgradient private well (Sabre-Piñon well, currently known as HMC-951) had background uranium concentrations. ARCO assumed that incoming fresh groundwater was diluting the contaminants to acceptable concentrations.

In 1989, ARCO began pumping groundwater from the alluvial and San Andres aquifers using wells located around the perimeter of the main tailings impoundment as part of an effort to reduce local contaminant concentrations to background levels. This attempt at remediation proved unsuccessful, as no reductions in constituent concentrations were observed. As a consequence, ARCO recommended establishing alternate concentration limits (ACLs) for the two aquifers (Applied Hydrology Associates Inc. 1990, 1995). Subsequently, NRC approved ACLs for uranium of 0.44 mg/L and 2.15 mg/L for point-of-compliance wells in the alluvial aquifer and San Andres aquifer, respectively. These approved levels were significantly below the New Mexico drinking water standard for uranium at the time, which was 5 mg/L. In 2004, New Mexico adopted the U.S. Environmental Protection Agency (EPA) drinking water MCL for uranium of 0.03 mg/L for groundwater. Consequently, the current MCL for uranium is significantly below the former MCL, which ARCO was required to meet, and substantially below the approved ACLs.

Assessments made by ARCO in the 1990s indicated that the highest uranium concentrations at the site would be observed in the San Andres aquifer north of the East-West Fault, and that uranium concentrations would continue to meet health-based requirements (<5 mg/L) beyond the site's east boundary. Sample data from recent years at wells along the east boundary indicate that ARCO's expectations are being met but that groundwater leaving the site exceeds the current uranium MCL.

2.2.4 Historical Groundwater Monitoring

Anaconda and ARCO monitored an extensive network of onsite and private offsite wells. ARCO decommissioned many of the onsite wells prior to transferring the site to DOE. Consequently, DOE inherited only nine of the ARCO onsite monitoring wells (Table 1), which were considered to be sufficient by ARCO and NRC to ensure regulatory compliance in the alluvial and San Andres aquifers. The LTSP (DOE 1997) lists these nine wells and associated monitoring requirements. Since 1997, groundwater quality issues have led DOE to install an additional 10 wells at the site. DOE continues to monitor all of the wells for the purpose of protecting human health and the environment. Although the water quality monitoring accounts for multiple contaminants, uranium is the sole constituent that exceeds regulatory standards at onsite wells. Uranium concentrations exceed the ACL in one alluvial well and exceed the MCL in both aquifers in several wells located in the east and south portions of the site.

Table 1. Monitoring Wells at the Bluewater Site in 1997

Well	Aquifer	Purpose of Well
E(M)	Alluvial	Background
F(M)	Alluvial	Point of Compliance
T(M)	Alluvial	Point of Compliance
X(M)	Alluvial	Point of Exposure
Y2(M)	Alluvial	Point of Compliance for PCB Monitoring
L(SG)	San Andres	Background
OBS-3	San Andres	Point of Compliance
S(SG)	San Andres	Point of Compliance
I(SG)	San Andres	Point of Exposure

2.3 Site Groundwater Monitoring System

DOE currently conducts groundwater monitoring at the Bluewater site twice a year. A total of 20 wells are sampled during each event. Figure 4 shows the monitoring locations, and Table 2 lists the wells and relevant construction information. In addition to the nine ARCO wells that DOE inherited in 1997 and the 10 wells that DOE installed in 2011 and 2012, DOE began to include offsite private well HMC-951 in 2013. HMC owns this well, which draws water from the San Andres aquifer and is located a short distance east of the Bluewater site entrance.

To assess the spatial extent of constituents of concern in areas surrounding the Bluewater site, DOE has sampled other offsite wells shown in Figure 5. The Simpson well was sampled in 2012, and the other private wells were sampled in 2013. No formal procedures determine which offsite wells are sampled or the frequency of offsite sampling. Depending on the purpose of the offsite sampling, DOE may attempt to occasionally resample these wells or sample alternative wells.

2.4 Homestake Mill Site

The Homestake site is about 5 mi north-northeast of Milan and about 3 mi east-southeast of the Bluewater site. In addition to a decommissioned mill, the site contains a large and a small tailings disposal cell. Both cells have a radon barrier with an overlying interim soil cover. The site also contains collection ponds, evaporation ponds, and a reverse osmosis water treatment system for groundwater remediation (Figure 6).

Tailings produced by the milling, which began in 1958, were deposited in the small and large tailings piles, which were unlined. The tailings were deposited on San Mateo Creek alluvium, which is about 100 ft thick at the site. Fluids seeping from the piles entered the alluvial aquifer and subsequently entered aquifers in sandstone units of the underlying Chinle Formation where those units are in contact with the alluvium.

HMC's long-term goal is to restore the alluvial aquifer and the Chinle Formation aquifers by reducing the concentrations of contaminants to background concentrations. Background concentrations for the aquifers were based on water quality of the aquifers in areas unaffected by site-generated contamination.

HMC has installed several hundred wells for groundwater extraction, water injection, and monitoring on and in the vicinity of the large tailings disposal cell. Water for the disposal cell injection wells, which is intended to push contaminated tailings leachate through the bottom of the disposal cell, is supplied by HMC-owned wells tapping the alluvial aquifer and relatively permeable layers in the Chinle Formation. A series of toe drains have been installed around the large tailings disposal cell to capture tailings fluids from both natural cell drainage and fluids pushed through the bottom of the cell.

A network of extraction wells in the alluvial aquifer south (downgradient) of the tailings disposal cells is operated to capture remnant groundwater contamination from milling and tailings leachate that has escaped the toe drains. These wells also capture San Mateo Creek alluvial aquifer groundwater flowing beneath the large tailings disposal cell from areas north of the Homestake site. A portion of the water collected by this system of wells is delivered to the reverse osmosis plant for treatment, and remaining pumped water is routed to the collection ponds. The treated effluent is re-injected into the alluvial aquifer and parts of the underlying Chinle Formation. The remaining pumped water is routed to the evaporation ponds. A series of injection wells and infiltration trenches placed along the perimeter of the groundwater extraction area are operated to prevent migration of contaminated groundwater farther to the south, in the direction of Milan.

HMC operates a second groundwater restoration system to remediate those portions of the groundwater contaminant plumes that have migrated off the mill site and beyond the influence of the primary groundwater collection and injection system. This system includes extraction of affected groundwater and land application treatment using an irrigation delivery network. The irrigation network consists of two center-pivot spray irrigation systems and two flood irrigation locations (Figure 6) and provides land application treatment of the collected contaminated groundwater. Irrigation is now permitted for only one center-pivot irrigation area.

Alluvial groundwater entering the Homestake site from the north has elevated levels of uranium and other constituents. Contaminant sources are erosion of uranium-bearing formations and historical contaminant releases from former uranium mines and mills in the San Mateo Creek drainage basin north of the Homestake site. This incoming contaminated groundwater complicates efforts to distinguish Homestake-related contamination from offsite sources.

Determination of contaminant provenance is also a concern in parts of the alluvial aquifer lying about midway between the Bluewater site and the Homestake site. As described in Chapter 4, a significant volume of contaminated San Mateo Creek alluvial groundwater flows directly west from the Homestake site; specifically, from the area under the large tailings disposal cell. In parts of the aquifer where these flows merge with southeastward flow in the Rio San Jose alluvium from the Bluewater site, it becomes difficult to identify respective sources of contamination. The combined flow of the two aquifer systems is to the southeast toward Milan (see Figure 22).

Table 2. Construction Information for Wells Monitored at the Bluewater Site

Well	Date Installed	Northing	Easting	Surface Elevation	Borehole Bottom Elevation	Borehole Diameter	Casing Top Elevation	Casing Bottom Elevation	Casing Diameter	Screen Top Elevation	Screen Bottom Elevation	Casing Depth	Borehole Depth	Depth to Screen	Screen Length
		(ft)	(ft)	(ft amsl)	(ft amsl)	(inches)	(ft amsl)	(ft amsl)	(inches)	(ft amsl)	(ft amsl)	(ft bgs)	(ft bgs)	(ft)	(ft)
San Andres Aquifer Wells															
11(SG)	7/14/2012	1558335.2	469874.8	6636.50	6330.80	8.5	6639.19	6339.00	4	6371.50	6341.50	300.19	305.7	265	30
13(SG)	6/27/2012	1546949.5	472765.8	6591.03	6276.63	8.5	6593.57	6288.53	4	6321.03	6291.03	305.04	314.4	270	30
14(SG)	7/11/2012	1548886.2	463599.0	6614.75	6279.55	8.5	6617.2	6297.35	4	6329.75	6299.75	319.85	335.2	285	30
15(SG)	6/18/2012	1550341.0	469224.4	6610.12	6222.12	8.5	6612.53	6236.77	4	6269.12	6239.12	375.76	388	341	30
16(SG)	6/14/2012	1553798.9	468714.9	6615.55	6380.55	8.5	6618.25	6388.05	4	6420.55	6390.55	230.2	235	195	30
18(SG)	6/7/2012	1547203.3	468136.1	6598.72	6293.72	8.5	6601.32	6306.32	4	6338.72	6308.72	295	305	260	30
I(SG)	7/23/1979	1552131.2	478106.1	6624.84	6294.84	7.875	6625.93	6389.84	5.56	6389.84[a]	6295.93[a]	236.09	330	236.09[a]	93.91[a]
L(SG)	1/18/1981	1553955.4	463034.6	6604.81	5994.81	9.88	6606.09	6192.81	5.56	6192.81[a]	5996.09[a]	413.28	610	413.28[a]	196.72[a]
S(SG)	2/13/1981	1553097.9	468775.2	6623.82	6287.82	7.875	6625.25	6343.82	8.62	6464.82	6343.82	281.43	336	159	121
OBS-3	2/6/1981	1554101.3	468776.2	6613.39	6250.39	6.5	6617.22	6260.39	5.56	6460.99	6263.39	356.83	363	152.4	197.6
HMC-951	2/1/1957	1545336.0	473124.1	6576.95	6301.95	12	6576.79	6334.79	10	6334.79[a]	6304.79[a]	242	272	242[a]	30[a]
Alluvial Aquifer Wells															
20(M)	7/19/2012	1551924.4	463734.8	6610.54	6481.04	10	6613.38	6483.04	4	6500.54	6485.54	130.34	129.5	110	15
21(M)	7/11/2011	1546974.1	472680.7	6590.85	6433.85	8.25	6593.8	6438.85	4	6451.25	6441.25	154.95	157	139.6	10
22(M)	7/14/2011	1548706.3	470929.9	6603.61	6450.61	8.25	6606.48	6454.36	4	6466.78	6456.78	152.12	153	136.8	10
23(M)	6/30/2012	1545333.7	472920.0	6576.6	6455.6	10	6579.22	6465.1	4	6487.6	6467.6	114.12	121	89	20
E(M)	5/31/1978	1548937.6	463534.8	6614.79	6514.79	7.875	6616.32	6581.79	4.5	6546.19	6524.99	34.53	100	68.6	21.2
F(M)	6/6/1978	1547617.6	468854.4	6602.22	6466.19	7.875	6603.59	6466.19	4.5	6508.02	6487.35	137.4	136.03	94.2	20.67
T(M)	11/16/1980	1550460.9	469141.1	6612.1	6470.1	6.5	6612.65	6477.1	4.5	6484.1	6479.1	135.55	142	128	5
X(M)	12/18/1980	1547948.8	472906.9	6597.04	6462.54	7.875	6598.91	6462.54	4.5	6474.04	6465.04	136.37	134.5	123	9
Y2(M)	9/11/1986	1548289.2	467531.8	6611.96	6481.96	8.75	6614.13	6485.96	4	6513.96	6488.96	128.17	130	98	25

amsl = above mean sea level; bgs = below ground surface; ft = feet
[a] Well screen was not installed; the borehole was left open below the bottom of the casing

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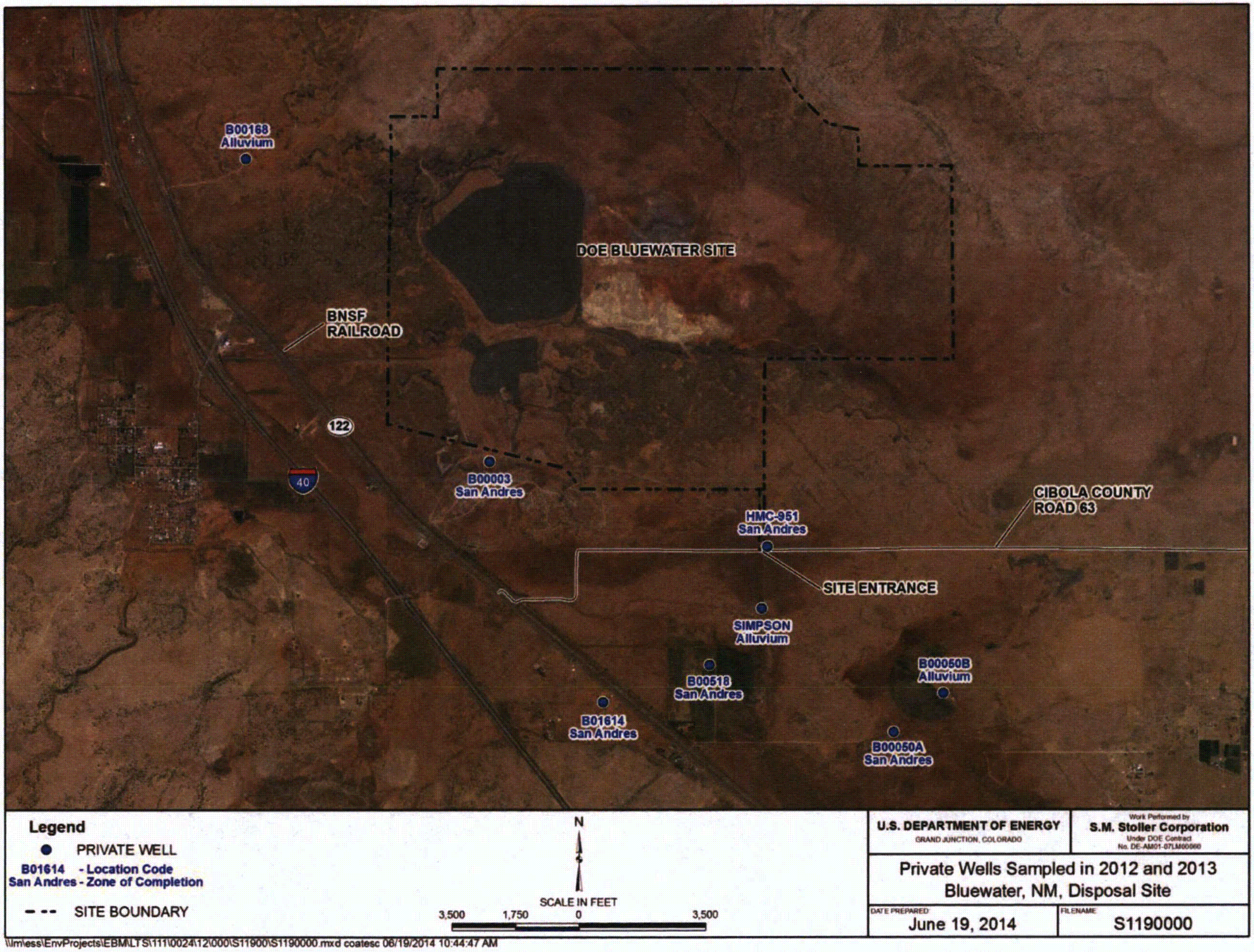

Figure 5. Private Offsite Wells Monitored by DOE

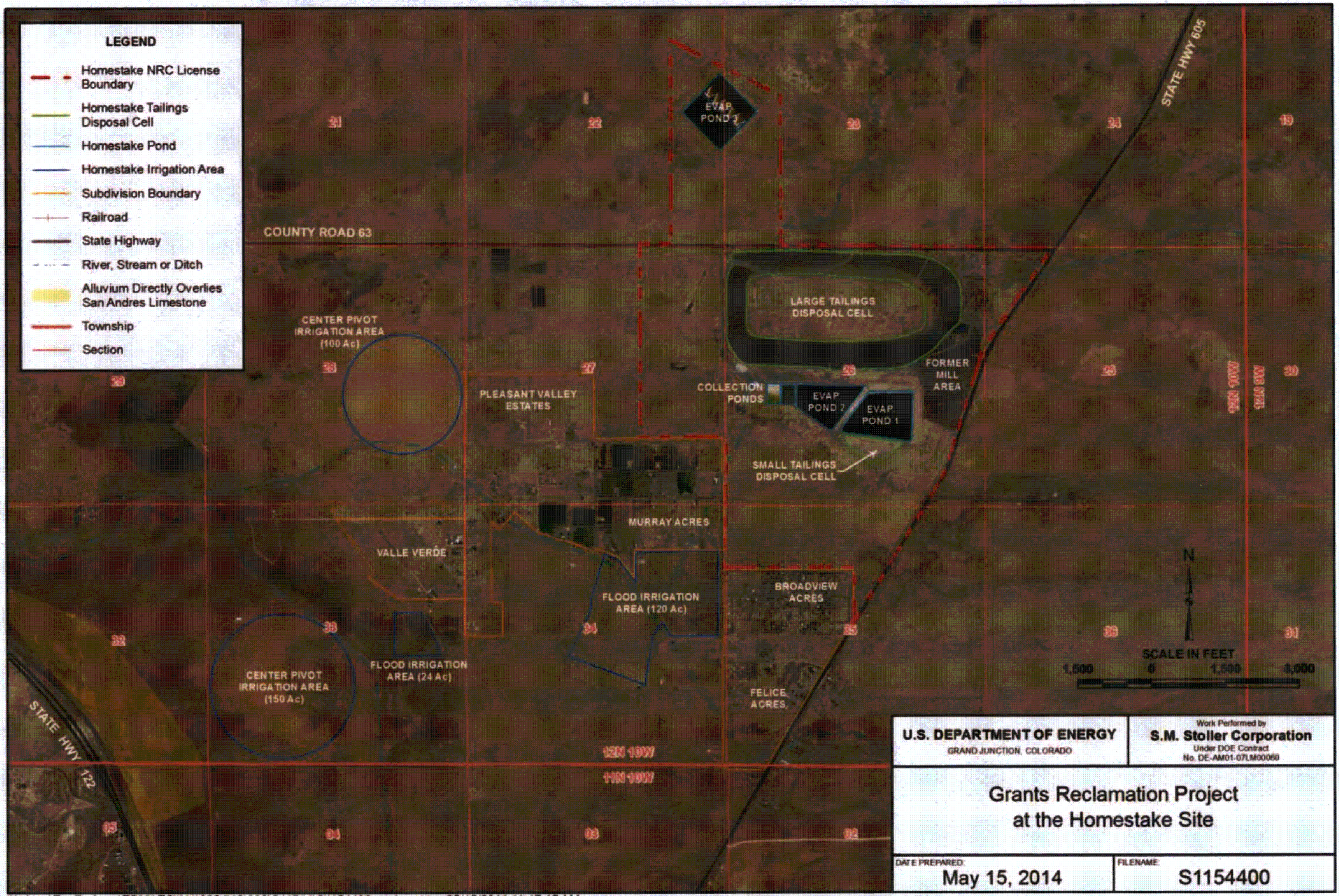

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Figure 6. Grants Reclamation Project at the Homestake Site

2.5 Regional Groundwater Monitoring

Aquifers within the study area were affected by uranium-milling operations at the Bluewater and Homestake sites and by mining and milling activities in the San Mateo Creek drainage basin. In addition to groundwater monitoring by DOE and HMC, the USGS and the New Mexico Environment Department (NMED) have historically monitored and continue to monitor wells in the Grants-Bluewater Valley. The communities of Bluewater, Milan, and Grants also monitor their groundwater supply well networks. Water level and constituent concentration data from these sources are included in the groundwater evaluations in this report.

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3.0 Geology

3.1 Geologic Mapping

Figure 7 and Figure 8 show regional and site geologic features, respectively. The regional geologic map, also shown at a scale of 1:48,000 in Plate 2, covers the study area and includes part of the Zuni Uplift, which is a recharge area for the San Andres aquifer. Also included in the regional map are downgradient and discharge areas for this aquifer in the Milan, Grants, and San Rafael areas. The site geologic map on a 2 ft topographic base, shown at a scale of 1:12,000 in Plate 3, covers about 8 square miles and includes the Bluewater site and bordering area. DOE geologists have verified many of the regional geologic features.

The regional geologic map was derived, with a few modifications, from the geohydrologic map by West (1972), which was mainly a compilation by Gordon (1961) of geologic mapping in the Grants-Bluewater area. Earlier, Gordon et al. (1960) with the USGS had completed the areal mapping and collection of detailed information on the water-supply wells; the later report by Gordon (1961) was a summary of the earlier work. Gordon et al. (1960) also mapped much of the area south of the Bluewater site (covering mainly the Milan and San Rafael 7.5-minute quadrangles) in the mid to late 1950s.

Other sources of geologic mapping that Gordon et al. (1960) included in their compiled map were work on other 7.5-minute quadrangles in the mid to late 1950s by the USGS in preliminary form by Thaden and Ostling (1967) for Bluewater, Thaden et al. (1967a) for Dos Lomas, and Thaden et al. (1967b) for Grants. Smaller-scale geologic maps that include and cover areas larger than the regional geologic map are available for the Grants 1:100,000-scale quadrangle (Dillinger 1990), the Albuquerque 1:250,000-scale quadrangle (Wyant and Olson 1978), and the Gallup 1:250,000-scale quadrangle (Hackman and Olson 1977); the southernmost part of the regional map is included in the 1:62,500-scale geologic map of the El Malpais lava field by Maxwell (1986).

Revised geologic mapping has recently been published for most of the regional geologic map area (7.5-minute quadrangles east of 108 degrees longitude). These new maps are a product of the STATEMAP program of the National Cooperative Geologic Mapping Act and were published by the New Mexico Bureau of Geology and Mineral Resources. The new maps are Bluewater (Rawling 2013), which includes most of the Bluewater site; Dos Lomas (Cather 2011); Grants (Zeiglar et al. 2012), which includes the Homestake site; and Milan (Rawling 2012). The San Rafael and Grants SE quadrangles along the south edge of the regional map have also been recently revised. Few changes are noted from the new geologic mapping on and near the Bluewater site (Bluewater, Dos Lomas, and Grants quadrangles). The most significant changes are in the Milan quadrangle, where geologic contacts and faults are more accurately shown. These changes are discussed in Sections 3.2 and 3.3.

3.2 Structure

3.2.1 Regional Structure

The site region is on the gently dipping northeastern flank of the Zuni Uplift (locally known as the Zuni Mountains), a northwest-striking structure with a complex tectonic history that developed during the latter part of the Laramide orogeny (Eocene time) along the south edge of the San Juan basin (Chapin and Cather 1981). The region is in the southeastern part of the larger Colorado Plateau physiographic province. Precambrian metamorphic and igneous rocks are exposed in the core (highest part) of the Zuni Uplift, and directly overlying Upper Paleozoic (Permian) sedimentary rocks gently dip northeast off the flank of the uplift. Sedimentary rocks of Permian and Triassic age, Neogene extrusive volcanic rocks, and Quaternary unconsolidated alluvial deposits in the regional and site areas are shown in the respective geologic maps (Figure 7 and Figure 8). Each sedimentary formation, volcanic rock unit, and Quaternary unit is discussed in detail in Section 3.3.

North- to northeast-striking faults are the most significant structural feature in the northern slope of the Zuni Uplift where the Bluewater site is located. Chamberlin and Anderson (1989) suggest that these faults are a result of Laramide indentation-extrusion tectonics. They describe this tectonic process as follows: as the Zuni block was being pushed north and northeast into the San Juan basin, large slivers of strata were shoved laterally to the east and west along strike-slip faults. These strike-slip normal and reverse faults bound large blocks. Several of these north- to northeast-striking faults are shown in the regional geologic map (Figure 7); from west to east, these faults are Big Draw, Ambrosia Lake, San Mateo (West and East branches), and San Rafael. The fault blocks are evident by the abrupt uplift and exposures of the Permian San Andres Limestone along the faulted boundaries of the blocks.

The Limekiln Canyon block, about 2 mi south of the Bluewater site, is a prominent northeasterly extrusion that has been uplifted and extruded north from the Zuni Uplift. Faults that bound the Limekiln Canyon block are the West branch of the San Mateo Fault to the southeast and what is probably a south extension (along Limekiln Canyon) of the Ambrosia Lake Fault to the northwest. These faults and two other north- to northeast-striking faults, Big Draw and the East branch of San Mateo, have vertically displaced sedimentary rocks as much as 100 to 300 ft along their lengths. Displacement along the San Rafael Fault is greater, ranging from about 200 ft in the Ojo del Gallo spring area to about 1,000 ft to the north in the Grants area (Frenzel 1992). Sedimentary rocks along the edges of the faulted blocks are drag folded and show monoclinal fold characteristics in places with dips as much as 30 degrees in the involved rocks.

Two other significant normal faults in the region that strike west and northwest displace sedimentary rocks by as much as 400 ft. The first fault, shown in Figure 7, extends from near the Mitchell Draw–Bluewater Creek confluence (which marks the start of the Rio San Jose) and extends southeast along the Rio San Jose valley to the West branch of the San Mateo Fault, and probably farther. This fault has about 250 ft of displacement at its northwest end about 1 to 2 mi northwest of Bluewater Village. This displacement is similar to the southeast along the fault, and the fault appears to abruptly displace the San Andres Limestone at the north ends of several of the extruded fault blocks (particularly the Limekiln Canyon block). Displacement along the downthrown side of this fault appears to have provided favorable topography for the course of the Rio San Jose.

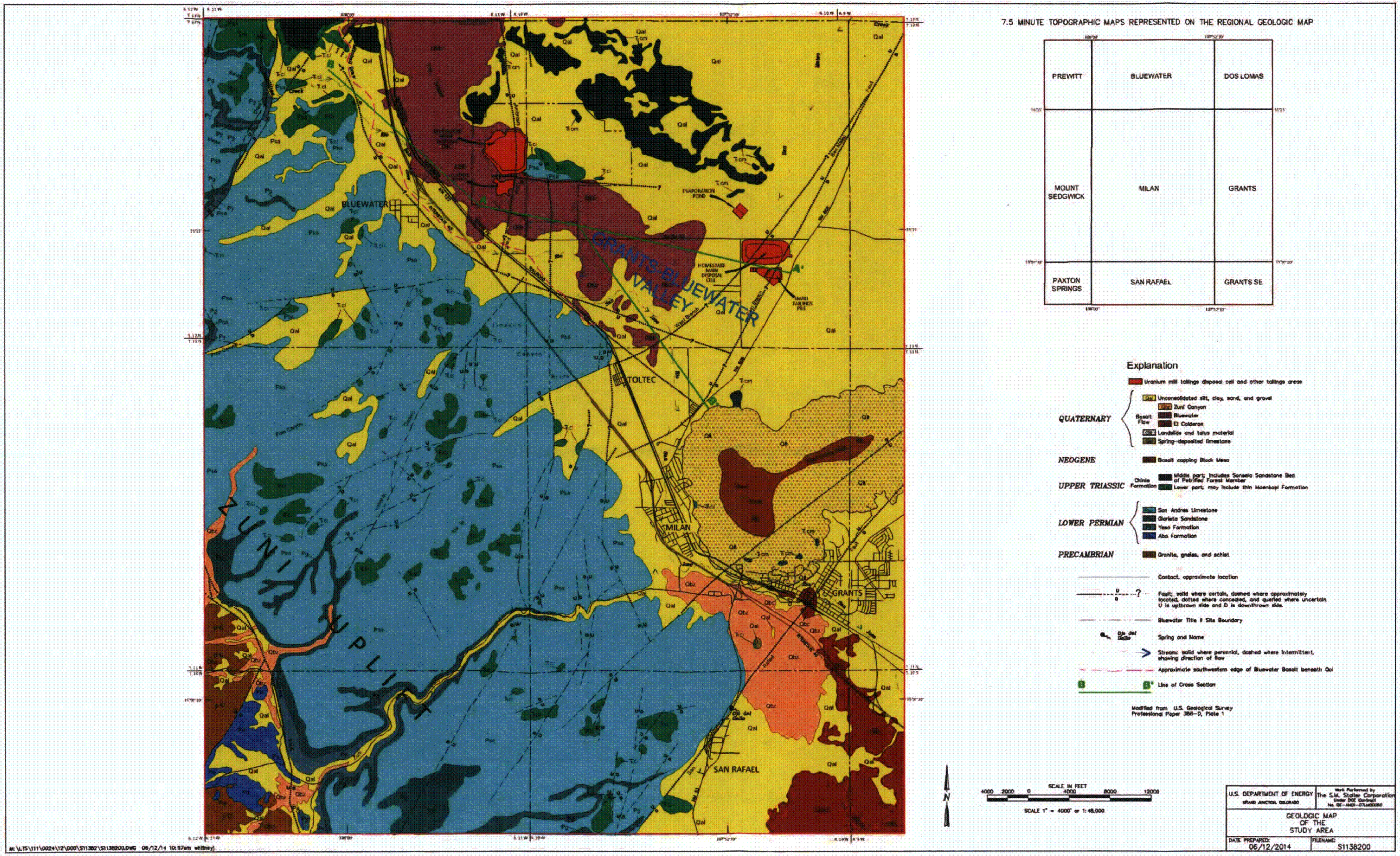

Figure 7. Geologic Features of the Study Area

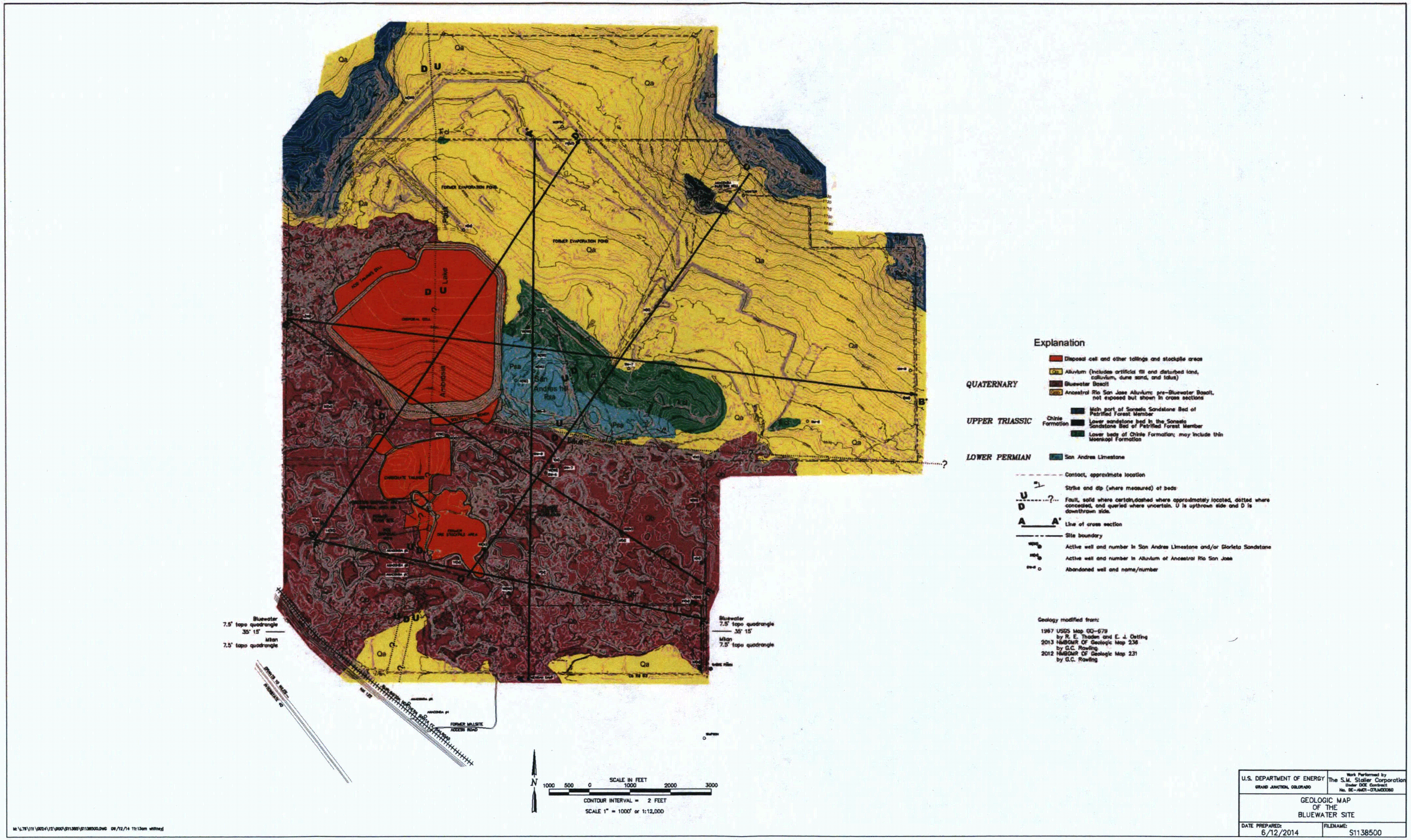

Figure 8. Geologic Features of the Bluewater Site

The second fault, shown in Figure 7 and in more detail in the site geologic map (Figure 8), is called the East-West Fault and extends for about 3 mi through the Bluewater site. On the north (upthrown) side of this high-angle normal fault, a block of resistant San Andres Limestone forms a prominent hill (San Andres hill) that rises up about 80 ft adjacent to the southeast corner of the main tailings impoundment. The west side of the resistant block is bounded by the Ambrosia Lake Fault, which intersects the East-West Fault.

Displacement on the East-West Fault is the largest (about 370 ft) in its western part near the southeast end of the Bluewater site main tailings disposal cell. Displacement decreases to the east; about 1 mi east, the displacement is about 270 ft, and about 2 mi to the east, displacement is uncertain and the fault may not extend much farther east. The East-West Fault may exist for about 0.5 mi or more west of the intersection of the Ambrosia Lake Fault, but its displacement is uncertain. Fault-created drag of the limestone and sandstone beds in the San Andres Limestone just north of the fault on San Andres hill has produced dips toward the south and southwest; dip of strata in this area away from the fault is typically about 3 degrees to the northeast.

The regional geologic map (Figure 7 and Plate 2) shows the locations of two geologic cross sections. The two cross sections are constructed along a northwest to southeast direction: one (A-A′) from the Bluewater site area southeast toward Milan and Grants, and the other (B-B′) from the mouth of Bluewater Creek to the Bluewater site area and eastward to the Homestake site. Figure 9 shows these two cross sections, and Plate 4 shows them in larger scale. Subsurface data for the sections were from borehole lithologic logs for holes drilled from the 1950s to wells installed by Homestake and DOE as recently as 2012. Surface data for the sections were from geologic mapping by Rawling (2012, 2013) and Zeiglar et al. (2012).

3.2.2 Site Structure

The Bluewater site geologic map (Figure 8 and Plate 3) shows the locations of six geologic cross sections. These cross sections show the complex structural variation within the site. Figure 10 shows three of the cross sections (A-A′, B-B′, and C-C′), and Figure 11 shows the other three (D-D′, E-E′, and F-F′). Plates 5 and 6 show larger-scale versions of the respective sections. Subsurface data for the sections were from borehole lithologic logs for holes drilled from the 1940s to DOE-installed wells in 2012. Surface data for the sections were from the site geologic map (Figure 8), which was compiled from recent geologic mapping by DOE geologists and geologic mapping by Thaden and Ostling (1967) and Rawling (2012, 2013). Cross sections A-A′ and C-C′ (Figure 10) show the displacement along the East-West Fault. Figure 12 shows a three-dimensional perspective (block diagram) of cross section A-A′.

Cross section B-B′ (Figure 10) and block diagram B-B′ (Figure 13) show the displacement along the north part of the Ambrosia Lake Fault. South of the East-West Fault, displacement along the Ambrosia Lake Fault is smaller; the fault may branch about 1 mile to the south, where different depths for the upper contact of the San Andres Limestone in Anaconda #2 and #5 wells suggest that the fault may split into two segments with a graben between them. Cross section F-F′ (Figure 11) and block diagram F-F′ (Figure 14) show the displacement across the southern part of the fault and the possible graben structure.

The Ambrosia Lake Fault may extend several miles farther south and join the fault in Limekiln Canyon, which bounds the northwest side of the Limekiln Canyon extruded block. North of the main tailings disposal cell, the Ambrosia Lake Fault is concealed, but its presence and relative displacement are implied by the location and attitude of sandstone beds at the northwest corner of the Bluewater site boundary. These sandstone beds in the Triassic Chinle Formation dip to the northwest as much as 25 degrees and represent drag on the downthrown side of the fault.

Four miles north of the disposal cell, the Ambrosia Lake Fault was the conduit for the Quaternary Bluewater Basalt flows, which emerged from the area of El Tintero cinder cone. This strike-slip fault, which Chamberlin and Anderson (1989) describe as a right-lateral shear zone, continues northward to the Ambrosia Lake area. Subsurface structural relations are highly uncertain in the area of the Bluewater site where the Ambrosia Lake and East-West Faults intersect. The only well control in this area are abandoned wells C(SG) and C(M), which were south of the East-West Fault and east of the Ambrosia Lake Fault. Interpretations of the complexity of this area are shown by the two cross sections D-D′ and E-E′ (Figure 11), and the perspective block diagram based on cross sections C-C′ and E-E′ (Figure 15).

A high-angle, north-northwest striking normal fault with about 20 to 25 ft of displacement (downthrown on the east) borders the east side of the San Andres hill north of the East-West Fault. Although the displacement on this fault is small, its surface trace is obvious and marked by the red siltstone beds of the lowermost Chinle Formation placed against the gray San Andres Limestone. Cross sections B-B′ and C-C′ (Figure 10) show the displacement across this fault. Thaden and Ostling (1967) and Gordon (1961) mapped this fault.

Only the three faults mentioned above (East-West, Ambrosia Lake, and the small normal fault on the east side of the San Andres hill) have been verified at the Bluewater site. The exact position and extent of the East-West and Ambrosia Lake Faults are uncertain: in many places, the Bluewater Basalt or alluvial material, or both, have covered geomorphic and geologic indications of faulting. Subsurface lithologic data from water wells and monitoring wells installed during the past 50 years have helped determine the approximate position and displacement of faults on the site. Additional drilling would be necessary to more precisely determine the position and displacement along the two major faults that cut through the site. Highest uncertainty on the site involving the faults is the area where the East-West and Ambrosia Lake Faults intersect beneath the south end of the main tailings disposal cell (Figure 8 and Plate 3).

Two evaluations of faulting at the site are more recent than the early fault mapping by Thaden and Ostling (1967) and Gordon (1961). The first, on the hydrogeology of the Bluewater site mill tailings impoundment area (Hydro-Search 1977), indicated on their Plate I of the site only the three faults verified by DOE. The second, by Dames & Moore (1981a), was in conjunction with an evaluation of seepage from a proposed subgrade tailings disposal area 1 to 2 mi east of the main tailings disposal cell. That evaluation investigated the validity of the numerous faults mapped in the site area earlier by Thaden and Ostling (1967) and Gordon (1961).

The Dames & Moore evaluation found no evidence for several of the earlier mapped faults, but the presence and approximate position of the Ambrosia Lake and East-West Faults was confirmed. Their revised fault location map is shown on their Plate C-2, which shows four faults south of the East-West Fault. The evidence for these four faults, which generally are the same as the ones mapped by Gordon (1961), was not given. The Bluewater Basalt covers these four faults, and no subsurface evidence from more recent boreholes can suggest their presence. Because of lack of evidence, it is doubtful that these four faults exist.

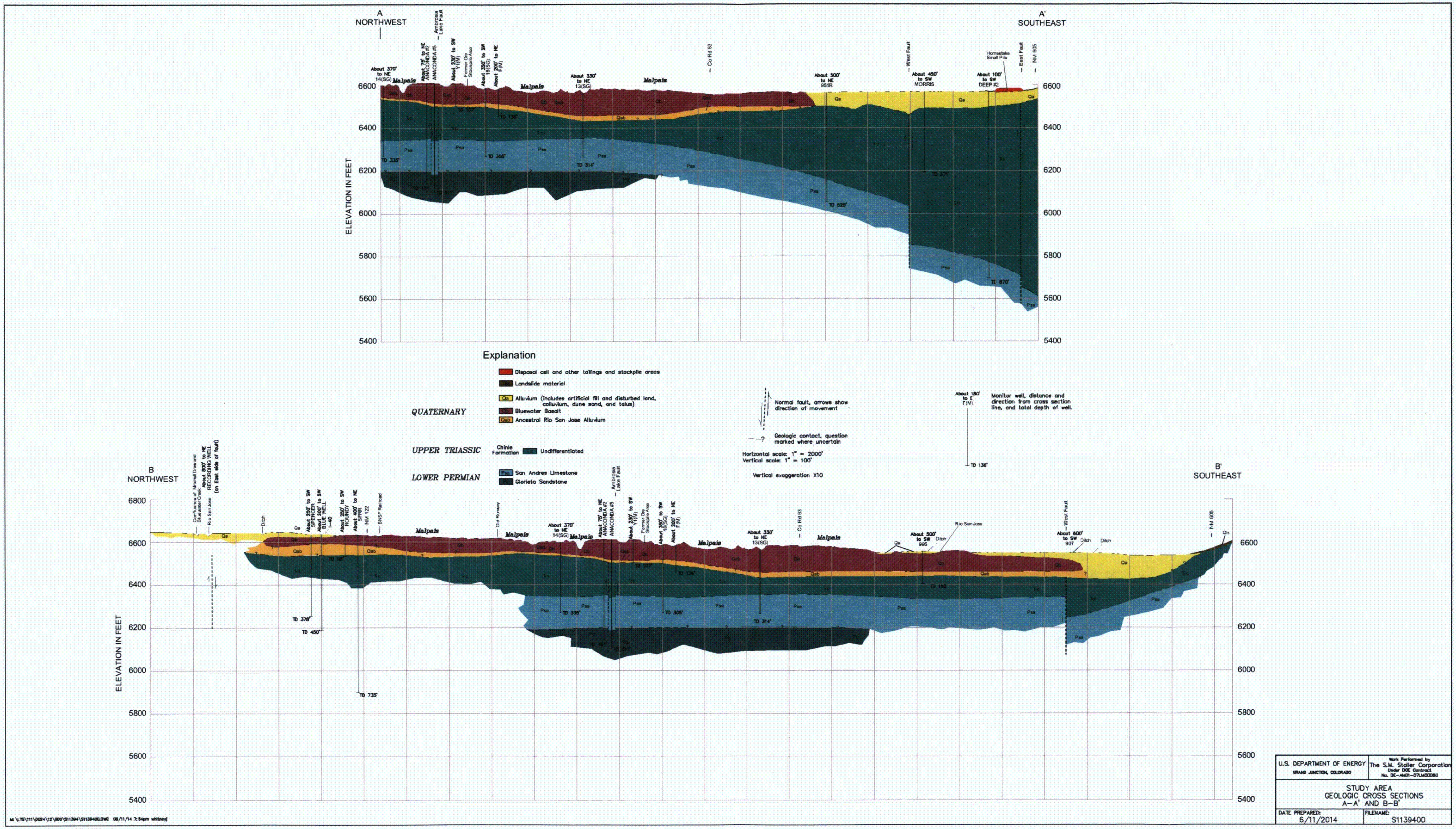

Figure 9. Study Area Geologic Cross Sections A-A' and B-B'

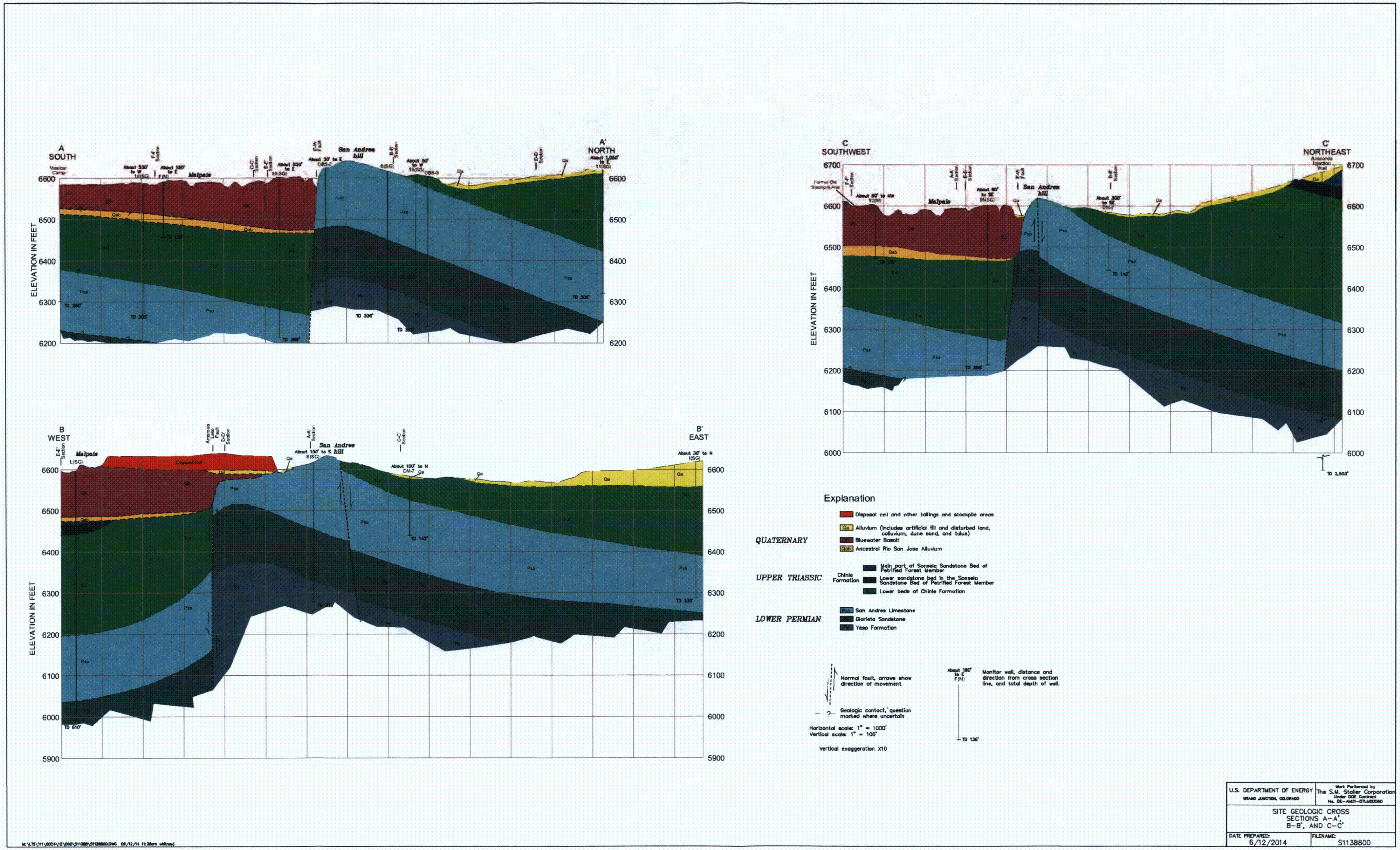

Figure 10. Site Geologic Cross Sections A-A', B-B', and C-C'

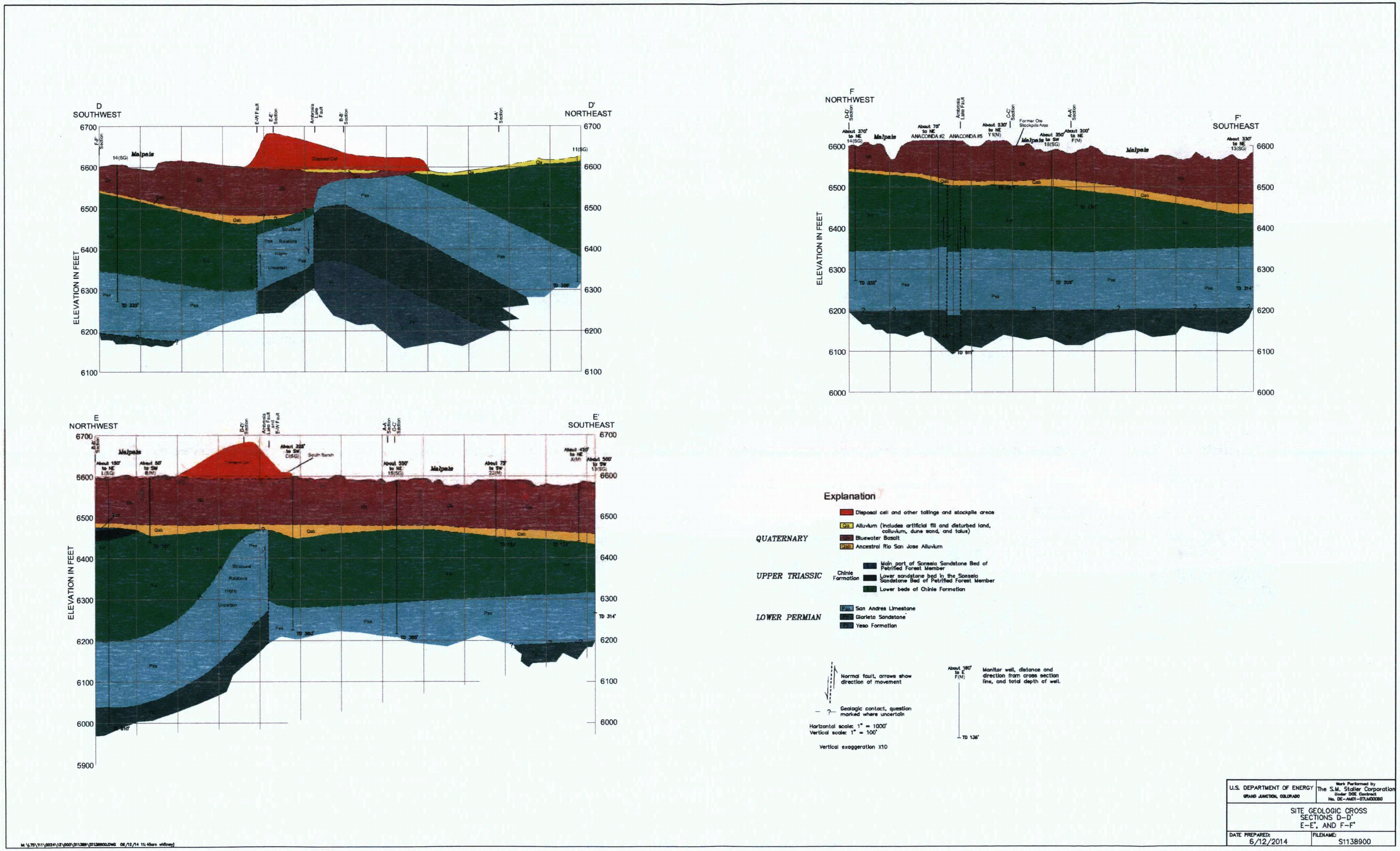

Figure 11. Site Geologic Cross Sections D-D', E-E', and F-F'

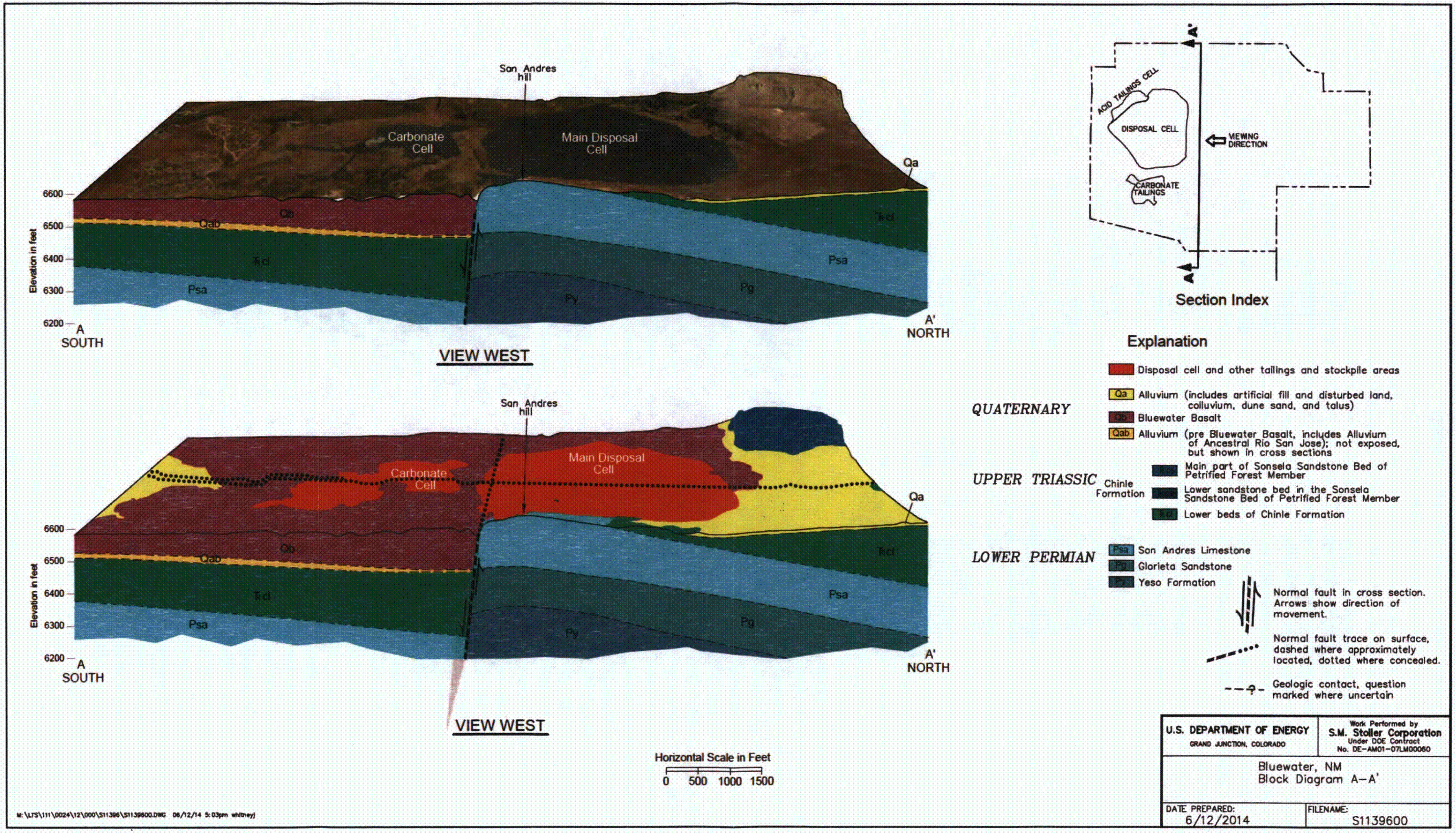

Figure 12. Block Diagram of Site Geologic Cross Section A-A'

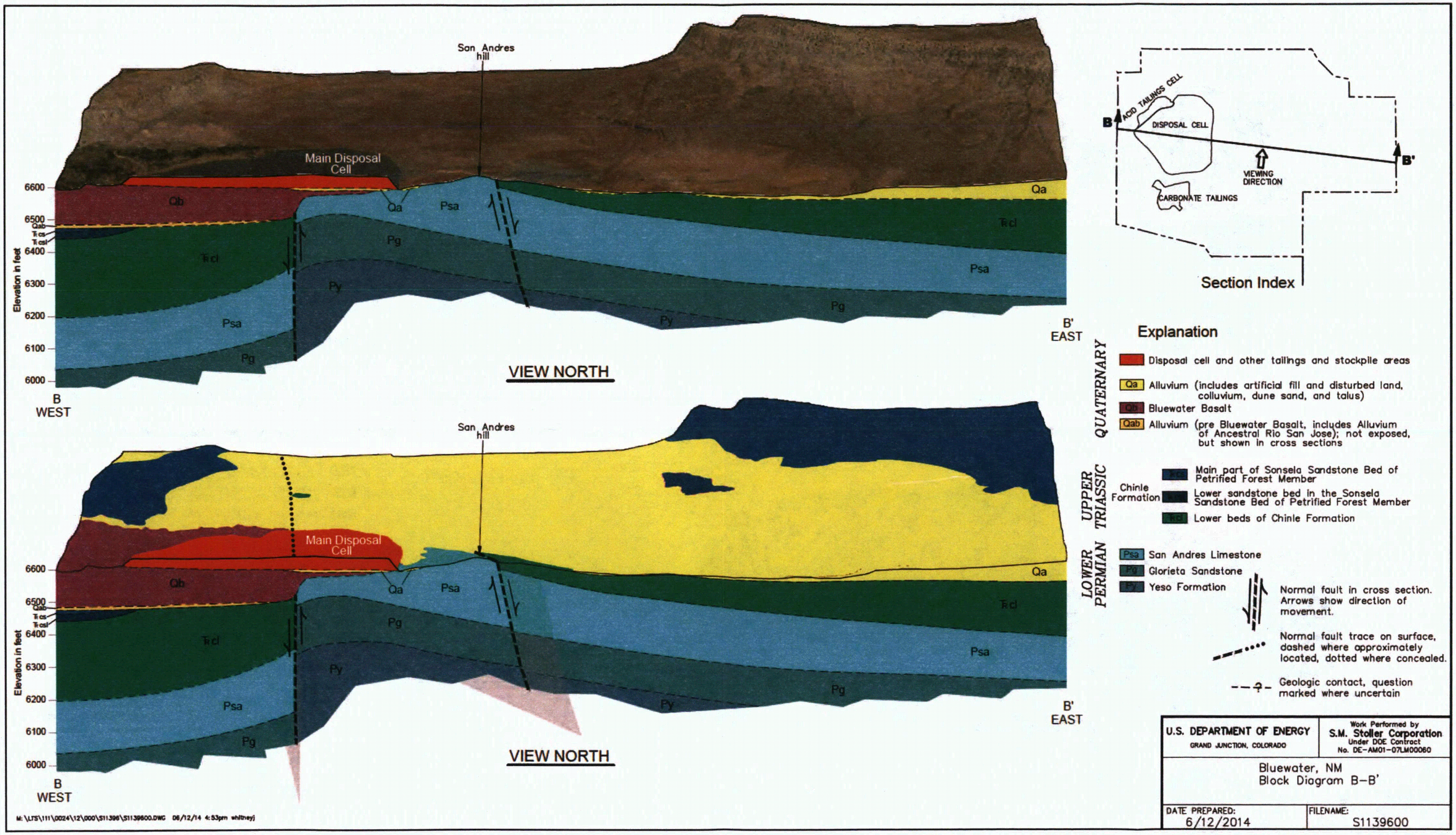

Figure 13. Block Diagram of Site Geologic Cross Section B-B'

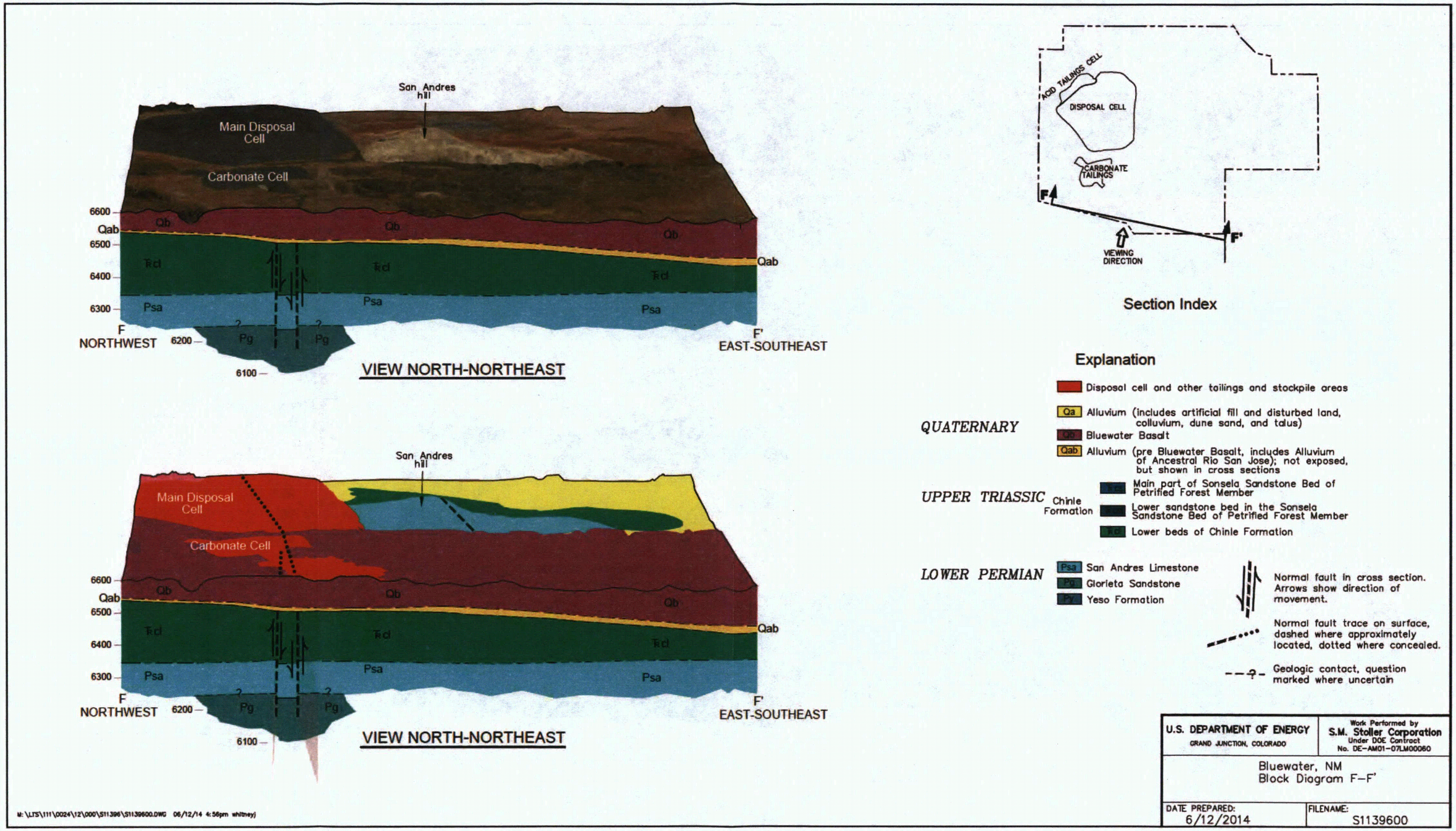

Figure 14. Block Diagram of Site Geologic Cross Section F-F'

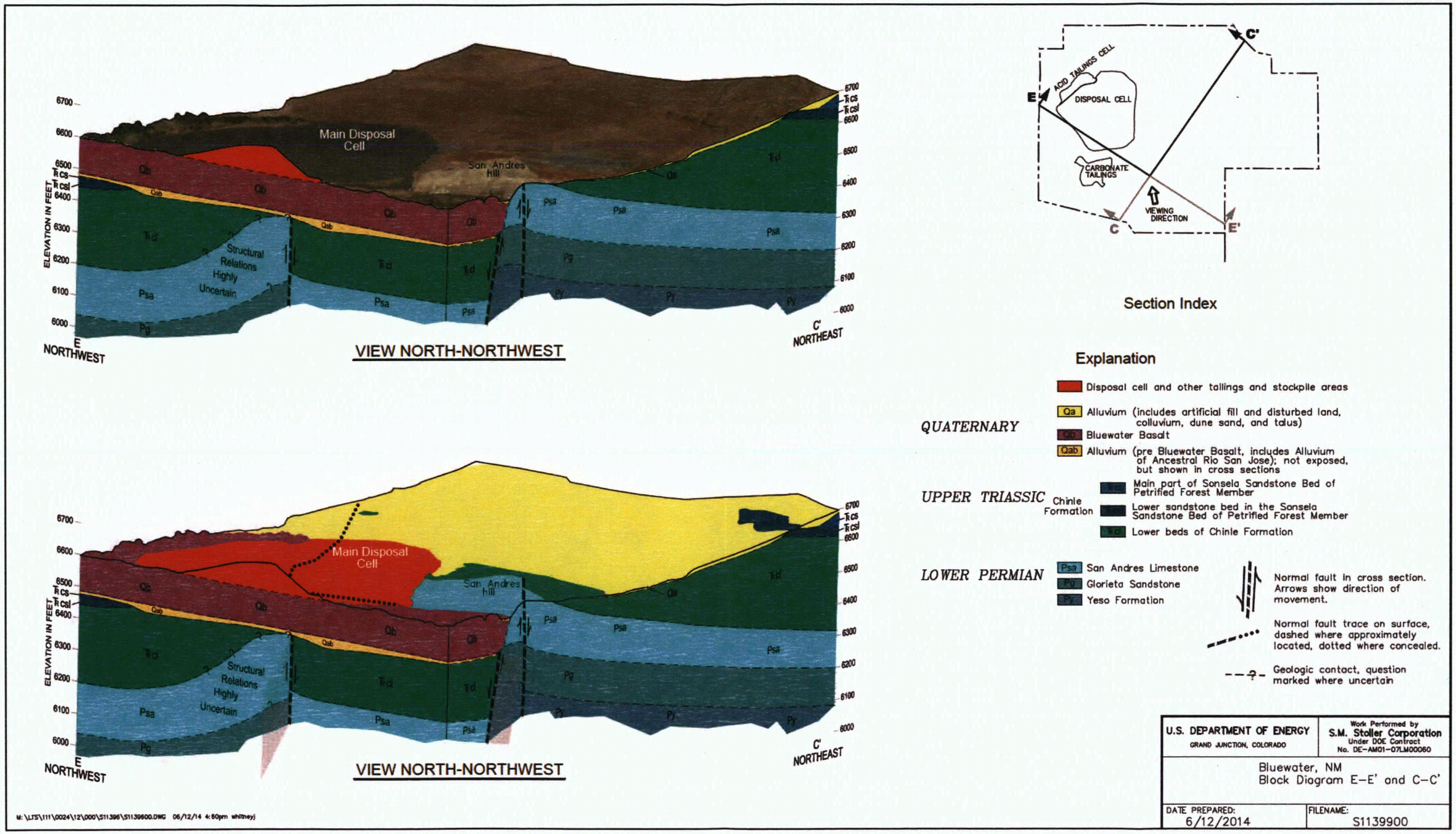

Figure 15. Perspective Block Diagram of Geologic Cross Sections C-C' and E-E'

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Dames & Moore (1981a) included joints in their field investigations. They measured orientations of 600 joints in the site area. About 200 joints were from the San Andres Limestone just north of the East-West Fault, and the remainder were from the Chinle Formation east of the site and in the northeast part of the site. They concluded that the joints were vertical or very nearly so, had an average spacing of about 3 ft, generally closed with depth, and were very tight to nonexistent in the subsurface.

Major and intermediate joint orientations in the San Andres Limestone are N. 66° E. (east-northeast) and N. 16° W. (north-northwest), respectively. DOE geologic investigations on the site in 2009 noted a general north-northwest strike of joints in the San Andres Limestone east of the San Andres hill. This direction is similar to the strike trend of the small normal fault on the east side of the San Andres hill. One major and two intermediate joint orientations in the Chinle Formation in the northeastern part of the site area are N. 46° E. (northeast), and N.86° W. (west) and N. 8° W. (north), respectively.

3.3 Stratigraphy

Geologic formations and units from Precambrian to Quaternary age exposed in the study area are described in this section. These formations are shown in the order of their geologic age in the Explanations for Figure 7 and Plate 2. An additional geologic unit that is buried and not exposed, but is described in this section, is the ancestral Rio San Jose alluvium of Quaternary age.

3.3.1 Precambrian Rocks

Basement metamorphic rocks of Paleoproterozoic age are exposed in the Zuni Mountains about 7.5 mi southwest of the Bluewater site in the core of the Zuni Uplift, as shown west of the Sedgwick Fault on the regional geologic map (Figure 7 and Plate 2). Much of the rocks are foliated calc-alkaline granitoids (mostly quartz monzonite) that are about 1,655 million years old (Timmons and Cikoski 2012). Also exposed are smaller areas of hornblende gneiss and felsic volcanic schist. Estimated depth to the Precambrian in the Bluewater site area is 1,500 to 2,500 ft; the depth to Precambrian at the Anaconda injection well was 2,432 ft (West 1972).

3.3.2 Permian Rocks

3.3.2.1 Abo Formation

The Lower Permian Abo Formation, which unconformably overlies Precambrian metamorphic basement rock, is a thick section of mixed siliciclastics ranging from mudstone to conglomerates. These sediments were deposited mainly in a floodplain environment and are exposed in the core of the Zuni Uplift where the formation is 500 to 800 ft thick. At the Anaconda injection well, shown in Figure 8 and Plate 3 and in cross section C-C′ in Figure 10 and Plate 5, the depth to the Abo Formation is 1,466 ft, and the formation is 770 ft thick (West 1972). Between the Abo Formation and Precambrian basement at the Anaconda injection well is 196 ft of the Pennsylvanian Madera Limestone (it is not present in the core of the Zuni Uplift and, therefore, is not described here).

3.3.2.2 Yeso Formation

Conformably overlying the Abo Formation, the Lower Permian Yeso Formation in the region consists of two members: the Meseta Blanco Sandstone Member and the overlying San Ysidro Member. The formation is exposed around the core of the Zuni Uplift, in some of the deeper canyons incised into the northeast flank of the uplift (such as in Zuni Canyon), and along the west (upthrown) side of the Big Draw Fault about 4 mi west of the Bluewater site. Deposited in a marginal marine to lagoonal environment, the Yeso Formation consists of cross-bedded, fine-grained, reddish-brown quartzose sandstone in its lower part, and cross-bedded, fine-grained clayey sandstone and siltstone with several thin limestone beds in its upper part. The formation grades upward into the Glorieta Sandstone. Not exposed at the Bluewater site, the Yeso Formation at the Anaconda injection well is 877 ft thick (West 1972).

3.3.2.3 Glorieta Sandstone

The Lower Permian Glorieta Sandstone is exposed in bold, yellow to light-brown cliffs in Bluewater and Zuni Canyons and in several other canyons along the northeast flank of the Zuni Uplift. Deposited in a marginal marine environment, the formation generally consists of light gray, fine- to medium-grained sandstone composed of well-sorted, rounded to subrounded quartz grains. Beds are thick and massive, with some tabular cross beds in the upper part of the formation. Calcareous-cemented beds are soft and friable in the lower part of the formation; some beds in the upper part of the formation may be hard owing to cementation by silica. A few greenish-gray clay interbeds separate the thick sandstone beds. The upper Glorieta intertongues with the overlying San Andres Limestone, and the top of the Glorieta is described as the base of the first limestone bed in the San Andres.

The Glorieta Sandstone does not crop out at the Bluewater site; however, it was penetrated by the Anaconda injection well as shown in cross section C-C′ (Figure 10 and Plate 5), where its thickness is 120 ft (West 1972). Three other wells (S(SG), OBS-2, and OBS-3) on the site penetrated the entire thickness of the Glorieta Sandstone. These wells are in the area of the uplifted San Andres hill and are shown in cross section A-A′ (Figure 10 and Plate 5); well S(SG) is also shown in cross section B-B′ (Figure 10 and Plate 5). At all three wells, the thickness of the Glorieta Sandstone is approximately 130 ft. The thickness of the Glorieta Sandstone increases to 150 to 200 ft to the west and south of the site in Bluewater and Zuni Canyons.

3.3.2.4 San Andres Limestone

The Lower Permian San Andres Limestone forms the extensive gray, dissected slope that dips gently off the northeast flank of the Zuni Uplift. Deposited in marine conditions on a shallow shelf environment, the San Andres Limestone consists of limestone, dolomite, sandstone, and chert. After deposition, a long period of erosion (approximately 25 to 40 million years) from Middle Permian to Middle Triassic time exposed the formation to extensive solution action resulting in development of karst topography in some of the limestone beds. Following this erosional event, which created a major regional unconformity, the thick red beds of the Upper Triassic Chinle Formation were deposited.

Formation thickness and amount of limestone in the San Andres Limestone vary across the region. The thickness varies from about 110 to 190 ft in the region, and the variation is due to the amount of pre-Triassic erosion and where the base and top of the formation are described. At the Anaconda injection well in the northeast part of the Bluewater site, the San Andres Limestone thickness is only 116 ft (West 1972), whereas the formation is typically 150 to 160 ft thick in wells in the central and western parts of the site. South of the Bluewater site on the flanks of the Zuni Uplift, the thickness increases to as much as 190 ft (Rawling 2012). The amount of limestone in the formation decreases with increasing distance north and northeast of the Zuni Uplift. At the injection well, the formation contains only about 10 percent limestone; in the central and south parts of the Bluewater site, limestone is about 30 to 40 percent of the formation; and to the south in the Milan quadrangle, limestone may be as much as 70 percent of the formation.

Gordon (1961) divided the San Andres Limestone into three informal members in the Grants-Bluewater area.

- **Lower member**—20 to 40 ft thick, composed of massive bluish-gray, dolomitic limestone, with interbedded sandstone and sandy limestone in the lower part.
- **Middle member**—15 to 30 ft thick, composed of light-gray to yellowish-buff sandstone that is well-sorted, friable, and locally cross-bedded.
- **Upper member**—60 to 100 ft thick, composed of massive gray, fossiliferous limestone, with the upper part being classified as sandy limestone in places and the occurrence of cherty material in some places.

These members are apparent in the lithologic log of core from the Anaconda #2 well (Gordon 1961). In that log, karstic cavities were reported from limestone in the lower and upper members. A thickness of 102 ft for the San Andres Limestone was shown in the Anaconda #2 well core log. Using the definition for the top of the underlying Glorieta Sandstone as the base of the first limestone bed, the base of the San Andres Limestone in the Anaconda #2 well core log was extended downward 51 ft to include interbeds of sandy limestone. This correction makes the thickness of the San Andres Limestone at the Anaconda #2 well at 153 ft. This thickness, along with a similar San Andres Limestone thickness of 150 ft penetrated by the Anaconda #5 well, is shown in cross section F-F′ (Figure 11 and Plate 6).

Nine wells in the Bluewater site area extended below the base of the San Andres Limestone. These wells are L(SG), S(SG), G(SG), D(SG), Anaconda #2, Anaconda #5, Anaconda injection well, OBS-2, and OBS-3. Of these, five (S(SG), G(SG), D(SG), OBS-2, and OBS-3) are in the area of the San Andres hill east of the main tailings disposal cell. Thicknesses of San Andres Limestone were used from these wells in construction of the six cross sections across the site. Other wells, which did not penetrate the entire thickness of the San Andres, provided data for the top of the formation that were useful for cross sections.

Several lithologic characteristics at the surface and in the subsurface identify the top of the San Andres Limestone at the regional Permian-Triassic unconformity. Surface characteristics include karst features and siliceous masses. Subsurface characteristics include abundant pyrite and color change.

- **Karst features:** Karstic solution processes and other erosion reportedly produced as much as 100 ft of relief in places on the surface at the top of the San Andres in and on the flanks of the Zuni.Uplift. Little or no karst relief on the erosion surface was seen in the Bluewater site area or the immediate surrounding region to the south. The most evident karstic solution features seen in the area are small-scale etching and fluting on outcrops of limestone and limey sandstone. These features were seen on outcrops at various levels through the San Andres Limestone thickness. In most places at the Bluewater site area, sandstone is exposed at the top of the San Andres Limestone, and karstic features had not developed.

- **Siliceous masses:** Silicification in the form of large, resistant masses of white to brown, iron-stained chert in thicknesses up to 5 ft are at scattered locations on the top of the San Andres Limestone. Two notable locations of the chert are at the Bluewater site on the uplifted San Andres hill and at the northeast end of the Limekiln Canyon block just southwest of State Highway 122. At both locations, the chert masses appear to be associated with an iron-stained sandstone bed that occurs at the top of the San Andres Limestone. It is possible that the chert masses filled channels cut into the top of the sandstone bed, but field exposures have not confirmed it. Only traces of chert have been found in drill cuttings from a few monitoring wells at the Bluewater site.
- **Abundant pyrite:** In most boreholes from monitoring well installations at the Bluewater site, drill cuttings from just below the top of the San Andres Limestone show an abrupt increase in fine-grained pyrite crystals. The abundant pyrite appears to be associated with fine-grained sandstone found at the top of the San Andres.
- **Color change:** Drill cuttings abruptly change color from brown-red, grayish-red, and greenish-gray of the lower Chinle Formation rocks to pale yellowish-brown and grayish-orange of uppermost sandstones in the San Andres Limestone. The yellow and orange color represents the oxidized conditions (increase in pyrite being oxidized, and limonite) in rocks of the San Andres Limestone below the unconformity.

3.3.3 Triassic Rocks

Triassic stratigraphy involving the Moenkopi and Chinle Formations is complicated in west-central New Mexico. During the past 50 years, improved understanding of regional stratigraphy has resulted in refinements in nomenclature. Heckert and Lucas (2003) present the current Triassic stratigraphic framework for the site region and the subdivision of the Chinle Formation (now Group status) into various formations. The older stratigraphic terminology of Gordon (1961) is used in this report because it is simple, and the important hydrologic units fit into its framework.

3.3.3.1 Moenkopi Formation

A small thickness of Middle Triassic Moenkopi Formation unconformably overlies the San Andres Limestone at the Bluewater site and southward on the flank of the Zuni Uplift. Thaden and Ostling (1967) mapped a 26 ft thickness of the formation, a reddish-brown arkosic and micaceous siltstone and sandstone, on the northeast flank of the San Andres hill on the Bluewater site. As much as 60 ft of Moenkopi Formation is shown in scattered remnants on the San Andres Limestone dip slope in recent mapping south of the Bluewater site in the Milan and San Rafael quadrangles (Rawling 2012, and Timmons and Cikowski 2012, respectively). Gordon (1961) did not think that the Moenkopi Formation extended this far east, and he mapped the red siltstone and sandstone directly overlying the San Andres Limestone as lower beds of the Chinle Formation. Because the thin Moenkopi Formation is not physically or chemically distinguishable from the overlying Chinle Formation, the Moenkopi is included in the lower beds of the Chinle Formation in the regional and site geologic maps and cross sections.

3.3.3.2 Chinle Formation

The Upper Triassic Chinle Formation is exposed or is present in subcrops along a wide northwest-striking valley (Grants-Bluewater Valley) from Grants to the Homestake and Bluewater sites. Most of the formation consists of grayish-red and reddish-brown mudstone, siltstone, and sandstone; lesser amounts of white to yellow and brown sandstone and conglomeratic sandstone are mainly in the middle and upper parts of the formation. The formation disconformably overlies the Moenkopi Formation, was deposited in a continental environment, and has an estimated thickness of 1,400 to 1,600 ft.

Only the lower and middle parts of the Chinle Formation, as mapped by Gordon (1961), are shown in the regional and site geologic maps. Upper parts of the Chinle Formation are not exposed in the study area; they occur along with other younger rocks northeast and downdip from the study area. Included in the lower part of the Chinle Formation is the thin Moenkopi Formation overlain by approximately 250 ft of predominantly red-brown claystone and siltstone. The middle part of the Chinle Formation, as described by Gordon (1961), consists of as much as 200 ft of thick beds of poorly sorted, cross-bedded sandstone and conglomeratic sandstone with interbeds of siltstone and mudstone. This sequence correlates with the Petrified Forest Member of the Chinle Formation, which Lucas and Hayden (1989) describe as the thick (about 1,000 ft) member in the middle of the Chinle. Specifically, within the Petrified Forest Member, the Sonsela Sandstone Bed (Sonsela), as much as 200 ft thick, is also described as consisting of light-gray to yellowish-brown, fine-grained to conglomeratic, cross-bedded sandstone with thin layers of grayish-purple mudstone (Lucas and Hayden 1989). Fossil (silicified) wood occurs in places in sandstone beds of the Sonsela, which crops out in the northwest portion of the Bluewater site. In the northeast part of the Bluewater site, a thick-bedded sandstone about 20 to 30 ft thick forms a conspicuous outcrop about 0.25 mi southwest of (and below) the main Sonsela outcrops. This white to pale-tan, cross-bedded sandstone is mapped as a lower sandstone bed within the Sonsela.

Much of the Chinle Formation in the region is covered by Quaternary unconsolidated alluvial, eolian (wind-deposited), and landslide material, or by one of four Neogene basalt flows. The lower part of the Chinle Formation is shown in the six cross sections for the site area and in the two cross sections for the region. The thickness of the lower part shown in the cross sections varies, depending on the degree of post-Triassic erosion. The entire thickness of the lower part of the Chinle Formation was penetrated in two wells (L(SG) and Anaconda injection well) at the Bluewater site. At well L(SG), the lower part of the Chinle Formation is nearly 250 ft thick, and about 25 ft of the overlying lower sandstone bed of the Sonsela also was penetrated (cross section B-B′ in Figure 10 and Plate 5, and cross section E-E′ in Figure 11 and Plate 6). At the Anaconda injection well, the lower part of the Chinle Formation is nearly 300 ft thick, and nearly 30 ft of the overlying lower sandstone of the Sonsela was penetrated (cross section C-C′ in Figure 10 and Plate 5).

Eastward from about 1 to 2 mi east of the Bluewater site entrance, the thickness of the Chinle Formation becomes much greater, owing in part to crossing to the downthrown sides of the West and East branches of the San Mateo Fault, as shown in regional cross section A-A′ (Figure 9 and Plate 4). In this area, lithologic borehole logs for the wells are not sufficiently detailed to allow the sandstones in the middle part of the Chinle Formation to be identified, and the larger thicknesses of the Chinle Formation are designated as undifferentiated. At the east end of regional cross section A-A′, just east of HMC's small tailings disposal cell, the thickness of the Chinle Formation is approximately 900 ft. HMC has identified three aquifers in the Chinle Formation in the subsurface vicinity of their site. These aquifers are in parts of the Chinle Formation that contain sandstone beds that dip to the northeast.

3.3.4 Neogene Volcanic Rocks

Three basalt flows within the Quaternary Zuni-Bandera volcanic field are represented in the region around the Bluewater site. These flows are, from oldest to youngest, El Calderon, Bluewater, and Zuni Canyon. An older basalt flow about 50 ft thick of Late Pliocene age, dated at approximately 2.5 million years old (Laughlin et al. 1993), is preserved as the cap on Black Mesa that rises 700 to 800 ft above Grants and Milan. The three Quaternary basalt flows that cover alluvial deposits in the Rio San Jose valley are discussed below.

3.3.4.1 El Calderon Flow

Referred by Gordon (1961) as the Laguna basalt flow, El Calderon flow is exposed in the Grants area and in the large area south of San Rafael known as El Malpais. It consists of a series of flows that originated at El Calderon center on the south side of the Zuni Mountains and extended for about 25 mi around the east side of the Zuni Uplift to the Grants area. The flows have been dated at 110,000 to 128,000 years old (Laughlin et al. 1993). Much of this basalt is covered by eolian sand and silt south of San Rafael.

3.3.4.2 Bluewater Basalt

El Tintero ("the inkwell"), a small scoria cinder cone on top of a small shield volcano about 4 mi north of the Bluewater main tailings disposal cell, was the source of the Bluewater basalt flows. Several flows—Thaden and Ostling (1967) indicated at least five, and Hydro-Search (1977) mapped two separate flows—erupted from El Tintero and coursed south and southeast, filling the ancestral valley of the Rio San Jose. The tholeiitic composition of the dense to vesicular basalt contains small olivine and plagioclase phenocrysts in a groundmass of plagioclase and clinopyroxene. The flows extended to their last surface exposure just northeast of Toltec; they may extend a small distance farther south in the subsurface, but probably did not reach Milan or the area covered by the younger Zuni Canyon flow. Figure 7 and Plate 2 show the approximate southwest edge of the basalt beneath the Quaternary alluvial material (from Hydro-Search 1977). Thickness of the basalt is variable; in the Bluewater site and nearby area, it is generally 70 to 130 ft, as shown in the cross sections in Figure 10 and Plate 5, and Figure 11 and Plate 6. Sims et al. (2007) determined that eruption of the Bluewater Basalt began approximately 68,000 years ago.

The exposed rough surface of the flow is referred to as El Malpais ("the badlands"), and many of the primary flow structures are still preserved. The upper surface of the flows commonly show collapse features and pressure ridges, and the flow edges in many places show a steep carapace of pahoehoe crust and hexagonal cooling joints. The upper parts of the flows typically contain more vesicles, the flows are fractured in places, and lava tubes and other void spaces are present. A lava tube was encountered during drilling of the initial borehole for well 20(M) in the west part of the Bluewater site in 2012.

3.3.4.3 Zuni Canyon Flow

The Zuni Canyon flow consists of alkali-olivine basalt that originated from the Paxton Springs volcano, a small scoria cone within the Precambrian crystalline rocks in the core of the Zuni Mountains. It occurs as scattered remnants in Zuni Canyon where it flowed northeast down the canyon and spread out on the valley floor of the Rio San Jose south and southeast of Milan. The flow is as much as 50 ft thick south of Milan where it displays characteristics typical of an aa flow, and it covers part of the older El Calderon flow southwest of Grants. The flow has been determined to be about 20,700 years old (Dunbar and Phillips 2004).

3.3.5 Quaternary Deposits

Two types of unconsolidated alluvial deposits are represented in the region around the Bluewater site: ancestral Rio San Jose alluvium and surficial alluvium. The ancestral Rio San Jose alluvium is not exposed because it was buried by the Bluewater Basalt flows. The surficial alluvium includes thin material that has covered parts of the basalt flows and thicker material that has accumulated in areas outside the basalt flows, including the San Mateo Creek alluvium. Other Quaternary deposits include landslide (and slump), talus, and colluvial deposits around the flanks of Black Mesa and a small area of spring-deposited limestone (travertine) between Grants and San Rafael. The two alluvial deposit types are described below.

3.3.5.1 Ancestral Rio San Jose Alluvium

During the Middle and Late Pleistocene, stream courses in the region (Rio San Jose and San Mateo Creek) eroded to depths of 150 to 200 ft below the elevation of the present land surface. The ancestral Rio San Jose channel, which was cut into beds of the lower part of the Chinle Formation, follows a sinuous path southeastward that was controlled in places by the position of faults and uplifted blocks of resistant San Andres Limestone. Geologic cross sections A-A′ and C-C′ in Figure 10 and Plate 5 show the relationship of the ancestral Rio San Jose channel to the uplifted block of San Andres Limestone on the Bluewater site.

Alluvium accumulated in and along the Rio San Jose channel and attained a thickness of as much as 30 ft prior to being covered by flows of Bluewater Basalt beginning about 68,000 years ago. The thickness of the alluvium varies across the ancestral Rio San Jose valley; thicknesses found during drilling to install monitoring wells at the Bluewater site range from just a few feet to approximately 25 ft.

Ancestral Rio San Jose alluvium, indicated on the geologic cross sections as Qab, consists mainly of sand and gravel. The coarsest material (bed load) is in the base of channels, which contain coarse sand and gravel (poorly rounded clasts as large as 1-inch diameter). Finer-grained material (medium- and fine-grained sand and silt) is in shallower parts of channels and laterally away from channels. Composition of the sediment represents the nearby parent materials. Coarser gravels are composed of limestone, chert, and sandstone fragments, and a few Precambrian metamorphic clasts derived mostly from the Zuni Uplift to the southwest. Finer-grained sands are arkosic and are derived mostly from the Chinle Formation. Some distinct beds of laterally continuous sands and gravels occur.

Along the east, south, and southwest margins of the Bluewater Basalt flows, the underlying ancestral Rio San Jose alluvium merges laterally with a thicker sequence of surficial alluvium. This subsurface relationship at the east and southeast ends of the basalt flows is shown in the regional geologic cross sections A-A′ and B-B′, respectively, in Figure 9 and Plate 4.

3.3.5.2 Surficial Alluvium

Shown as Qal on the regional geologic map (Figure 7 and Plate 2) and Qa on the Bluewater site geologic map (Figure 8 and Plate 3), surficial alluvium consists of sand, gravel, and clay-silt deposited in fluvial (river), eolian, and lacustrine (lake) environments from the Middle Pleistocene to the present. Thickness is variable, depending on the presence or absence of basalt flows. Where basalt flows are not present, the alluvium may be 100 to 150 ft thick, as in the Homestake site area (represented by the San Mateo Creek alluvium), the area between Toltec and Milan, and the area northwest of the Bluewater site along the course of the present Rio San Jose north of Bluewater Village. In these areas, the age of the lowest part of the alluvium extends back to at least Middle Pleistocene time.

Fluvial deposits are generally sand to gravel sized and are represented along the present courses of the Rio San Jose, San Mateo Creek, the stream in Zuni Canyon, Bluewater Creek, and Mitchell Draw. Material from eolian deposition is Holocene age, is generally silt, covers parts of basalt flows, and covers the surface of open expanses such as the San Mateo Creek valley and the area north and northeast of the Bluewater main tailings disposal cell. Lacustrine deposition, of clay-silt size, is not exposed but is represented in the subsurface around and north of the Homestake site where the terminus of the Bluewater Basalt flows periodically blocked or dammed the flow of San Mateo Creek, creating intermittent lakes or playas. The Zuni Canyon basalt flow may have created a similar lacustrine depositional environment when it reached the valley of the Rio San Jose and likely blocked its flow.

4.0 Regional Hydrology

4.1 Surface Water

Streams in the study area include Bluewater Creek, Mitchell Draw, Rio San Jose, and San Mateo Creek. With the exception of Bluewater Creek, most reaches of the watercourses are dry throughout each year, largely because of the semiarid to arid climate of west-central New Mexico. Surface water flow in stream channels tends to occur only during large precipitation events in the region. The Rio San Jose, the dominant watercourse in the study area, has the potential under natural (undeveloped) conditions to maintain surface water flow along several miles of its main channel. However, flows in the river are rarely seen, primarily because it is heavily used for agriculture. Irrigation diversions of water from Bluewater Creek, the main source of flow to the Rio San Jose, cause most of the river between about 2 mi upstream of Bluewater Village and a few miles downstream of Grants to remain dry most of the time. As a result, the Rio San Jose is generally considered to be an ephemeral stream within the study area.

As previously mentioned, Bluewater Creek (Figure 3) is the only stream in the study area that tends to maintain perennial flows. The creek flows into Bluewater Canyon from Bluewater Lake, a reservoir about 5.5 mi upstream from where the creek empties into the Grants-Bluewater Valley. Flows in Bluewater Creek are diverted into an irrigation canal system about 0.5 mi south of the mouth of Bluewater Canyon at the base of the Zuni Mountains. About 1.3 mi downstream of the diversion structure (Figure 3), the Bluewater Creek channel joins Mitchell Draw, a typically ephemeral watercourse, to form the Rio San Jose. The combination of limited flows in both Mitchell Draw and Bluewater Creek downstream of the irrigation diversions explains the mostly ephemeral nature of the Rio San Jose in the Grants-Bluewater Valley.

In the northeast corner of the study area, the 4.5-mile reach of San Mateo Creek between the Cibola-McKinley county line and the large tailings disposal cell at GRP is considered an ephemeral stream. Six to 11 mi upstream of this reach, near and downstream of the community of San Mateo, the creek is fed by several springs, making year-round streamflow possible. El Rito Creek, also fed by springs, is a significant tributary to San Mateo Creek in this area (Figure 2). However, downstream of the confluence of the two creeks, seepage losses and water diversions for various purposes tend to limit flows in the main channel of San Mateo Creek. Farther downstream and about 3.5 mi north of the Cibola-McKinley county line, Arroyo del Puerto, an ephemeral watercourse that drains from the Ambrosia Lake mining area, is a significant tributary to San Mateo Creek. Because San Mateo Creek is ephemeral in the study area as well as just north of the Cibola-McKinley county line, surface water flows within the creek's drainage reach as far south as the Homestake site only during major flood events.

Despite the limited amount of surface water flow in the study area, surface watercourses have an impact on the hydrology of the Grants-Bluewater Valley. Seepage losses from Bluewater Lake and Bluewater Creek contribute recharge to both the alluvial aquifer and the San Andres aquifer. In addition, seepage losses from the irrigation canals fed by Bluewater Creek constitute recharge sources from about 3.5 mi north of Bluewater Village to variable distances downstream of the village. Unlike the reach of Bluewater Creek between the outlet of Bluewater Lake and the Grants-Bluewater Valley, the remaining watercourses draining the northeast flank of the Zuni Mountains are ephemeral. However, seepage losses from these drainages contribute significantly to groundwater recharge, especially in the San Andres aquifer near the base of the mountains.

Though San Mateo Creek is typically dry for several miles north of the Homestake site, the creek does play a role in the hydrology of the Grants-Bluewater Valley. Occasional floodwaters in the creek's drainage seep into underlying alluvium, contributing recharge to alluvial aquifer groundwater flowing south-southwestward to the Homestake site.

Historically, a spring called Ojo del Gallo, just north of San Rafael (Figure 3), was a significant source of surface water flow in the study area. In the 1930s, discharge from the spring of about 7 cubic feet per second (cfs) was common. Flow from Ojo del Gallo began declining in the mid-1940s due to increasing groundwater pumping for irrigation. During the period 1946 to 1953, flow from the spring decreased from about 4.5 cfs to a rate that was insufficient for irrigation of gardens (Baldwin and Anderholm 1992). Discharge from the spring was absent from 1954 to 1982, but some flow did return to the spring's outlet in the mid-1980s. Virtually no flow has been observed at Ojo del Gallo during the past two decades.

Discharges at Ojo del Gallo (Figure 3) are caused by blockage of southward-migrating groundwater in the San Andres aquifer due to vertical offset of geologic units at the San Rafael Fault (Frenzel 1992). The flows from the spring have changed with time because of variable hydrologic stresses on the San Andres aquifer. Above-average precipitation in the study area can result in more recharge to the aquifer, which increases the spring's discharge, whereas years of low precipitation and recharge to the aquifer cause decreases in spring flow. Similarly, decreases in hydraulic head due to extensive groundwater pumping in the region, which began in the mid-1940s and increased in the 1950s, reduces discharge at Ojo del Gallo.

4.2 Hydrogeologic Units

Given the limited flows in streams within the study area, groundwater is the most dependable and most heavily accessed source of water in Cibola County. Sections 4.2.1 through 4.2.7 describe the roles that geologic formations in the study area play in forming the regional groundwater system.

4.2.1 Quaternary Alluvium

The alluvial aquifer in the Grants-Bluewater Valley consists primarily of Quaternary-age alluvium. The expression "alluvial aquifer" is also sometimes used to describe saturated subsurface flow within both the alluvium and overlying basalt.

Other than the extraction of alluvial groundwater for remediation purposes at the GRP, most of the water withdrawn from the alluvial aquifer is for agricultural needs. In much of the study area, saturated alluvium rests on the Chinle Formation, which is generally considered to be an aquitard. Accordingly, the alluvial aquifer is not in direct hydraulic connection with the San Andres aquifer in parts of the Grants-Bluewater Valley where the Chinle Formation is present. In areas where the Chinle Formation is absent, the alluvium lies directly on the San Andres Limestone, facilitating direct hydraulic connection between the two aquifers. Near the base of the Zuni Mountains, the Chinle Formation is mostly absent. The occurrence of alluvium directly overlying the San Andres Limestone depends on the location of and vertical displacement of strata along faults.

The alluvial aquifer occurs in three general areas. Much of the aquifer consists of sands, gravels, silts, and clays deposited along a northwest-southeast alignment beneath and adjacent to the current channel of the Rio San Jose, near the base of the Zuni Mountains. These sediments are referred to in this report as recent Rio San Jose alluvium, or recent river alluvium. The area containing recent river alluvium is several miles long, extending from near the confluence of Bluewater Creek and Mitchell Draw to the east end of Grants. The thickness of the recent river alluvium varies from about 100 to 150 ft. A geologic map prepared by Hydro-Search (1981a) for the Grants-Bluewater Valley suggested that recent river alluvium in areas at the base of the mountains west of the Bluewater site directly overlie the San Andres Limestone. Such areas of direct contact between the alluvium and the San Andres Limestone are found at the mouth of Bluewater Canyon and near Bluewater Village. A much larger area in which alluvium appears to directly overlie the San Andres Limestone at the base of the mountains occurs from about 1 mi north of Toltec to about 1 mi south of Milan (Plate 7).

Another major portion of the alluvial aquifer occurs within sediments that were deposited by the ancestral Rio San Jose and are now covered by Bluewater Basalt. Lying northeast of the recent Rio San Jose alluvium, these deposits are called ancestral Rio San Jose alluvium, or ancestral river alluvium. The ancestral Rio San Jose alluvium extends southeastward from the north boundary of the study area to areas underneath the Bluewater site, and terminates about 4 mi east-southeast of the main tailings impoundment, near the West Branch of the San Mateo Fault. The thickness of the ancestral river alluvium at wells in the vicinity of the Bluewater site ranges from about 5 to 35 ft.

The third area containing alluvial sediments considered part of the regional alluvial aquifer is associated with San Mateo Creek, in the east half of the Grants-Bluewater Valley. This alluvium was deposited by San Mateo Creek over thousands of years and is commonly referred to as San Mateo Creek alluvium. Much of the alluvium associated with the creek consists of materials eroded from the Chinle Formation and younger formations in the drainage basin, including uranium-ore-bearing formations. The San Mateo Creek alluvium extends from the northeast corner of the study area to the GRP, and then on to the Rio San Jose just north of Milan. Saturated alluvium upgradient of the GRP is about 1.5 to 2 mi wide, and it expands to about 3 to 4 mi wide in the vicinity of the large tailings disposal cell at the Homestake site. Near its intersection with ancestral and recent Rio San Jose alluvium, the San Mateo Creek alluvium is as much as 5 mi wide. However, a significant portion of the subsurface in this widened portion of the alluvium is unsaturated due to the presence of a buried ridge of the Chinle Formation, which is the bedrock underlying the alluvium in the GRP. The thickness of San Mateo Creek alluvium in the vicinity of the Homestake site varies from about 50 to 150 ft, and saturated thickness in the alluvium at and near the Homestake site ranges from 0 to about 100 ft.

The transmissivity of the alluvial aquifer varies widely depending primarily on the grain size and the saturated thickness of the alluvial sediments. Aquifer-test data collected from pumping and monitoring wells in the Grants-Bluewater Valley indicate that the aquifer's transmissivity ranges from about 50 to 350,000 square feet per day (ft^2/day). Dividing these values by corresponding aquifer thicknesses at sites where aquifer tests have been performed results in aquifer hydraulic conductivities that range from 0.2 ft/day to 700 ft/day. Estimated hydraulic conductivities for alluvium in the vicinity of the Bluewater site range from 75 to 150 ft/day. Reported values for hydraulic conductivity of San Mateo Creek alluvium tend to be lower than those ascribed to alluvium deposited by the ancestral and recent Rio San Jose and typically range from

10 to 70 ft/day. However, hydraulic conductivities as large as 300 ft/day have been measured in a paleochannel containing San Mateo Creek alluvium directly west of the large tailings disposal cell at the Homestake site (HMC 2012).

The higher values of hydraulic conductivity in recent and ancestral Rio San Jose alluvium are associated with high-energy sand and gravel deposits along paleochannels of the river, whereas the lower values of hydraulic conductivity are attributed to finer-grained deposits in non-channel, overbank environments. The paleochannel containing San Mateo Creek alluvium just west of the large tailings disposal cell at the Homestake site also contains sands and gravels deposited in a high-energy fluvial environment.

The alluvial aquifer has been described as unconfined in some locations and confined in others. Confined conditions appear to occur where groundwater levels in ancestral Rio San Jose alluvium exceed the base elevation of overlying Bluewater Basalt. Relatively large depths to saturated alluvium (100 ft or more) at the Homestake site, including areas miles to the north of the large tailings disposal cell, suggest that groundwater in San Mateo Creek alluvium might be at least partially confined by shallower, less permeable strata (e.g., lacustrine deposits). In contrast, unconfined conditions would be expected where depth to groundwater is small (e.g., less than 30 ft), or where the water level in ancestral Rio San Jose alluvium falls below the base elevation of overlying Bluewater Basalt.

Where unconfined, the alluvial aquifer's specific yield is between 0.1 and 0.25 (dimensionless). Where confined, the storativity of the alluvial aquifer is reported to be about 1×10^{-3} (dimensionless). Numerous livestock and domestic (drinking water or household use) wells are completed in Quaternary alluvium (Baldwin and Anderholm 1992).

4.2.2 Basalts

In areas where hydraulic heads in ancestral river alluvium are higher than the base of overlying Bluewater Basalt, groundwater has the potential to flow horizontally within both the alluvium and the basalt. Such combined flow becomes apparent where the basalt is relatively permeable due to presence of fractures. Saturated volcanic rock in such areas is capable of yielding large quantities of water to wells. In some reports that discuss the hydrology of the Grants-Bluewater Valley, the coupled alluvium and basalt are referred to as the basalt-alluvium aquifer, whereas in others, they are simply called the alluvial aquifer. The latter convention is used in this report. In areas where the permeability of the basalt is very low, the basalt tends to act more as a confining layer for the underlying alluvium rather than an extended part of the alluvial aquifer.

Historically, saturated basalt in the region has been an important water resource. Springs reportedly issue from basalts along the margins of mesas near Grants (Baldwin and Rankin 1995), providing water for stock and domestic use.

4.2.3 Chinle Formation

The Chinle Formation generally acts as a confining unit, or aquitard, between the alluvial aquifer and the San Andres aquifer. The capacity of the Chinle to locally confine groundwater in the San Andres aquifer depends on its thickness and lithology. In areas where the San Andres aquifer is confined, the clay content within the Chinle causes the rocks to deform and squeeze in, thus preventing upward or downward flow of groundwater across the formation (Baldwin and Anderholm 1992). The tendency of clay zones in the Chinle to squeeze in on fractures has been observed during the drilling of test holes that penetrate as deep as the San Andres Limestone.

In much of the study area, the Chinle Formation is unsaturated because of its low permeability. Where it is saturated, the Chinle is typically too fine-grained to transmit sufficient water to be considered an aquifer. However, water yields from some of the more sandy units of the Chinle are sometimes adequate for supplying domestic or stock water (Baldwin and Anderholm 1992).

Hydraulic properties of the Chinle Formation are based on reported values in hydrologic literature. Reported values for hydraulic conductivity in a formation of this kind are highly variable, ranging from 10^{-8} to 0.1 ft/day (Baldwin and Rankin 1995). Recharge to Chinle rocks in areas where it is possible occurs mostly by downward seepage of alluvial aquifer water into upper parts of the formation. Some seepage of water through the Chinle Formation (inter-aquifer leakage) is reported to occur near the base of the Zuni Mountains, in areas where the Chinle is relatively thin. Studies of the San Andres aquifer by the USGS (e.g., Baldwin and Anderholm 1992) suggest that pumping groundwater from the aquifer in areas where it underlies Chinle Formation rock has the potential to induce downward seepage of Chinle Formation water into the pumped horizons.

4.2.4 San Andres Aquifer

The San Andres aquifer is the most productive aquifer in the study area and the primary water source for municipal, commercial, irrigation, domestic, and livestock uses. The San Andres Limestone and the Glorieta Sandstone are generally treated as one aquifer, partly because the contact between them is gradational and difficult to identify. In addition, good hydraulic connection between the two units suggests that they can be collectively thought of as a single aquifer.

Though the San Andres Limestone is called a limestone, it consists mostly of sandstone in the vicinity of the Bluewater site. A map of limestone thicknesses in White and Kelly (1989) indicates that the cumulative thickness of limestone facies in the formation near Bluewater Village is less than 50 ft, with the remaining thickness of the San Andres Limestone consisting of sandstone facies. Given that the thickness of the San Andres Limestone in the vicinity of the Bluewater site varies between about 120 and 160 ft, sandstone in the formation at and near the site generally constitutes more than half the full formation thickness Though sandstone is more prevalent than limestone in the San Andres aquifer in the study area, regional and local hydrogeologic studies indicate that the largest amounts of water in the San Andres Limestone, and the San Andres aquifer as a whole, are transmitted in solution channels, cavernous zones, and fractures, which are characteristic of a karst environment. The channels, zones, and fractures appear to be well connected in the Grants-Bluewater Valley and are most developed near the Zuni Mountains. Karst features are abundant near the base of the mountains because limestone there was subjected to weathering, dissolution, and fracturing during periods of uplift and exposure (White and Kelly 1989). Areas of the San Andres Limestone farther from and north of the mountains have been less affected by these processes.

Karst horizons in the San Andres Limestone are attributed to geologic events of significant erosion (White and Kelly 1989). One such event occurred at the conclusion of the Permian

Period, which eventually helped lead to the filling of solution channels and cavities by Chinle Formation sediments. In some parts of the study area, prolonged erosion removed most or all of the San Andres Limestone and exposed the Glorieta Sandstone prior to deposition of Chinle materials in Triassic time. Erosion removed much of the upper part of the San Andres Limestone where it is exposed east of the main tailings impoundment and just north of the East-West Fault.

The combined thickness of the San Andres Limestone and the Glorieta Sandstone at the Bluewater site generally varies between about 250 and 350 ft (see Section 5.3). For calculation purposes, the mean thickness for the combined formations is assumed in this chapter to be 300 ft. Though porous medium flow of groundwater through the sandstones of the Glorieta is not as large as flow through solution channels in limestones of the San Andres, the sandstones are nevertheless much more permeable than regional formations dominated by shales, siltstones, and evaporite facies and are thus capable of transmitting relatively large quantities of subsurface water. In addition, fractures in the Glorieta Sandstone add secondary permeability, increasing the amount of flow through the sandstone.

Aquifer testing performed at wells screened in the San Andres aquifer typically attribute measured transmissivities to the combined thickness of the San Andres Limestone and Glorieta Sandstone, despite the fact that many wells in the aquifer tap only the uppermost 40 to 50 ft of the San Andres Limestone. Estimated transmissivity values from the testing are highly variable, ranging from 10 to 450,000 ft^2/day (Frenzel 1992, Baldwin and Rankin 1995). Using aquifer-test results, information on lithology of and saturated thicknesses in San Andres aquifer sediments, and potentiometric surface maps for the aquifer, Baldwin and Anderholm (1992) divided their region of study into seven transmissivity zones. Of those, two zones apply to almost the entire study area. A third transmissivity zone relevant to this conceptual model study is located in the southeast corner of the study area, on the southeast side of the San Rafael Fault.

One of the transmissivity zones identified by Baldwin and Anderholm (1992) occupies a north-south trending area on the west side of the Ambrosia Lake Fault that is about 5 mi wide (from Ambrosia Lake Fault to within a mile of the study area's west boundary). Though hydraulic testing of a well in this zone yielded a transmissivity of 24,000 ft^2/day, the zone was assigned a representative transmissivity of 10,000 ft^2/day. Baldwin and Anderholm (1992) surmised that wells drilled in this area west of the Bluewater site would not encounter a significant amount of limestone, and that the transmissivity values used to represent it were generally reflective of the Glorieta Sandstone, including fractured sandstone.

The San Andres aquifer transmissivity zone located east of the Ambrosia Lake Fault has some of the highest transmissivity values identified by Baldwin and Anderholm (1992), with the largest value being 450,000 ft^2/day. Extending east-southeastward to the San Rafael Fault, this zone was considered one of the most permeable due to the presence of cavernous zones, solution channels, and fractures in the aquifer. Reported well yields in this part of the study area can be as large as 2,800 gallons per minute (gpm), which is equivalent to 6.25 cfs. Though such pumping rates tend to be observed in wells that are associated with some of the largest transmissivity values measured in the aquifer, hydraulic testing at other wells in this zone resulted in estimated transmissivities as small as 100 ft^2/day. This demonstrated that San Andres aquifer transmissivities in the area lying between the Bluewater site and Grants can be quite variable. A map of posted aquifer-test results in Baldwin and Anderholm (1992) suggested that the largest transmissivity values are encountered near the base of the Zuni Mountains, and values become less with distance north of the mountains. A transmissivity of 50,000 ft^2/day was considered by Baldwin and Anderholm (1992) to be representative of the transmissivity zone between the Ambrosia Lake Fault and Grants.

Baldwin and Anderholm (1992) reported that calculated transmissivity values for the zone in the southeast corner of the study area ranged from 70 to 200,000 ft^2/day. The larger transmissivity values were again attributed to cavernous or highly fractured zones in limestone. In addition to the large transmissivities identified through aquifer hydraulic testing, physical evidence for cavernous limestone rock was seen in some wells drilled in areas east of the San Rafael Fault. However, the wells with such physical evidence were outside the study area, either to the east or south of the study area's border. Baldwin and Anderholm (1992) selected a transmissivity of 50,000 ft^2/day as being representative of this zone.

Estimated hydraulic conductivities for the San Andres aquifer in the Grants-Bluewater Valley vary from about 0.25 to 1,800 ft/day (Baldwin and Rankin 1995). In comparison, Freeze and Cherry (1979) reported that a range of 1 to 10,000 ft/day is representative of hydraulic conductivity of cavernous limestone. Compilations of hydraulic properties for numerous karst aquifers presented in Huntoon (1995) and Worthington and Ford (2009) suggest that hydraulic conductivities in most cases range from 1 to about 3,000 ft/day.

In most parts of the study area, groundwater flow in the San Andres aquifer occurs under confined conditions. The aquifer storage parameter of interest in a confined aquifer is storativity, whereas the relevant storage parameter in an unconfined aquifer is specific yield. Storativity is calculated as the product of the aquifer's thickness and its specific storage, the latter of which is defined as the volume of water released from storage from a unit volume of aquifer under a unit decline in hydraulic head. USGS studies of the San Andres aquifer (Baldwin and Anderholm 1992, Frenzel 1992) reported that measured storativity values from aquifer hydraulic tests at wells screened in the San Andres aquifer were frequently on the order of 1×10^{-4} to 5×10^{-4}, and that the full range of measured storativities was from about 5×10^{-5} to 0.01. The high end of this range is relatively large for storativity and is probably more representative of a specific yield at a well that tends to respond to aquifer stresses, such as pumping, as if it were unconfined. In contrast, the low storativity value in the cited range is reflective of water being released from a confined aquifer because its matrix and the groundwater in it are slightly compressible. Dividing the low storativity value in the cited range by 300 ft, the estimated thickness of the San Andres aquifer at the Bluewater site, results in a specific storage of 1.7×10^{-7} ft^{-1}. This value is typical of specific storage in unfractured sandstones (Freeze and Cherry 1979).

The effective porosity of an aquifer affects the rate at which groundwater moves through it. Hydrologic assessments of the San Andres aquifer in the past have used variable estimates of its effective porosity, ranging from 0.02 to 0.25. The low end of this range was chosen to represent secondary permeability and porosity features of limestone that contains fractures and solution channels (Dames & Moore 1984a, 1986a). In comparison, the maximum value for the effective porosity is usually meant to be representative of water migrating in the pores between individual sand grains in unfractured sandstone layers. For a given hydraulic conductivity and horizontal hydraulic gradient, calculation of the average linear velocity of groundwater using the maximum value of effective porosity results in a value that is much lower than the water velocity in solution channels and fractures within limestone.

It is important in this conceptual model study to account for the highest velocities of groundwater in the San Andres aquifer, since these high velocities dictate when contaminants are first observed at specific locations downgradient of the Bluewater site, which lie east and southeast of the site. With this understanding, calculated velocities in limestone containing fractures and solution channels are best estimated using effective porosities that are relatively small, such as less than or equal to 0.05. Calculated velocities in fractured sandstone are also best estimated using relatively low effective porosities because most of the cross-sectional area of flow in fractured sandstone is typically taken up by matrix as opposed to fractures. In contrast, use of the high effective porosity of 0.25 mentioned above is probably more appropriate for estimating groundwater velocity in unfractured sandstone within the San Andres aquifer. However, it is also likely that the effective porosity of unfractured sandstone in portions of the San Andres aquifer is lower than 0.25 due to the presence of calcareous and silica cements between individual sand grains (e.g., see Section 3.3.2.3).

Rather than assuming that a single value of hydraulic conductivity and a single effective porosity apply to the entire vertical thickness of the San Andres aquifer at any given location, it is assumed in this conceptual model study that these parameters vary, both increasing and decreasing, with depth in the aquifer. With this conceptualization, horizontal water velocities and contaminant concentrations will also vary with depth in the aquifer. As a result, the contaminant concentration measured at a well screened over the full aquifer thickness at a location downgradient of a contaminant source will represent a mixture of different concentrations that are fed into the well at different rates. An assessment of estimated average linear velocities in the San Andres aquifer in Section 4.3.3.2 further examines how variable hydraulic properties of the aquifer media affect rates of transport to specific locations east and south of the Bluewater site.

4.2.5 Yeso Formation

The Yeso Formation is not a major source of groundwater in Cibola County. Reported transmissivities for the formation tend to be less than 1,000 ft^2/day (Baldwin and Anderholm 1992), indicating that hydraulic conductivity values for the formation are typically low. Water-level and well-yield data are generally not available for the Yeso Formation.

4.2.6 Abo Formation

The Abo Formation is not a significant source of water in the study area, largely because of low permeabilities and high mineral contents in anhydrite and gypsum strata composing much of this bedrock unit. The Abo Formation occurs at depths greater than 3,000 ft in much of the study area (Baldwin and Rankin 1995), which hinders attempts to drill wells into the formation in search of a groundwater resource. Attempts to measure hydraulic conductivity in the Abo and Yeso formations have resulted in estimates that range from 1×10^{-4} to 0.01 ft/day (Baldwin and Anderholm 1992).