LMS/GNO/S09337

2012 Groundwater Monitoring and Inspection Report Gnome-Coach, New Mexico, Site

March 2013

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Abbreviations

bgs	below ground surface
BSZ	bottom of screen zone
DOE	U.S. Department of Energy
DTW	depth to water
EPA	U.S. Environmental Protection Agency
ft	feet
LM	Office of Legacy Management
LTHMP	Long-Term Hydrologic Monitoring Program
pCi/L	picocuries per liter
SGZ	surface ground zero
TOC	top of casing
TSZ	top of screen zone

Executive Summary

Gnome-Coach was the site of a 3-kiloton underground nuclear test conducted in 1961. Surface and subsurface contamination resulted from the underground nuclear testing, post-test drilling, and a groundwater tracer test performed at the site. Surface reclamation and remediation began after the underground testing. A Completion Report was prepared, and the State of New Mexico is currently proceeding with a conditional certificate of completion for the surface. Subsurface corrective action activities began in 1972 and have generally consisted of annual sampling and monitoring of wells near the site. In 2008, the annual site inspections were refined to include hydraulic head monitoring and collection of samples from groundwater monitoring wells onsite using the low-flow sampling method. These activities were conducted during this monitoring period on January 18, 2012. Analytical results from this sampling event indicate that concentrations of tritium, strontium-90, and cesium-137 were generally consistent with concentrations from historical sampling events. The exceptions are the decreases in concentrations of strontium-90 in samples from wells USGS-4 and USGS-8, which were more than 2.5 times lower than last year's results. Well USGS-1 provides water for livestock belonging to area ranchers, and a dedicated submersible pump cycles on and off to maintain a constant volume in a nearby water tank. Water levels in wells USGS-4 and USGS-8 respond to the on/off cycling of the water supply pumping from well USGS-1. Well LRL-7 was not sampled in January, and water levels were still increasing when the transducer data were downloaded in September. A seismic reflection survey was also conducted this year. The survey acquired approximately 13.9 miles of seismic reflection data along 7 profiles on and near the site. These activities were conducted from February 23 through March 10, 2012. The site roads, monitoring well heads, and the monument at surface ground zero were in good condition at the time of the site inspection. However, it was reported in September 2012 that the USGS-1 well head had been damaged by a water truck in April 2012.

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1.0 Introduction

This report presents the 2012 groundwater monitoring results collected by the U.S. Department of Energy (DOE) Office of Legacy Management (LM) at the Gnome-Coach, New Mexico, Site (Figure 1). Groundwater monitoring consisted of collecting hydraulic head data and groundwater samples from the onsite wells. This report summarizes groundwater monitoring and site investigation activities that were conducted at the site during the fiscal year 2012.

2.0 Site Location and Background

The site consists of 640 acres of federally withdrawn lands approximately 25 miles east of Carlsbad in Eddy County, New Mexico (Figure 1). The site was the location of the first underground nuclear test performed under the Plowshare Program by the U.S. Atomic Energy Commission, a predecessor to DOE. The Plowshare Program was a research and development initiative started in 1958 to determine the technical and economic feasibility of peaceful applications of nuclear energy. The underground nuclear test conducted at the site was identified as Project Gnome and was performed on December 10, 1961. The test consisted of detonating a nuclear device with an estimated yield of 3 kilotons at a depth of 1,184 feet (ft) below ground surface (bgs) in a bedded salt deposit known as the Salado Formation. Immediately following the detonation, close-in stemming materials failed, and gases from the cavity vented to the atmosphere through the access shaft and tunnel (Rawson et al. 1964). Post-test drilling operations and preparations for another underground nuclear test, identified as Coach, began shortly after the Project Gnome test. The Coach experiment was initially scheduled for 1963 but was canceled and never executed.

No additional underground nuclear detonations occurred at the site; however, in 1963, the U.S. Geological Survey conducted a groundwater tracer test using four dissolved radionuclides—tritium, iodine-131, strontium-90, and cesium-137—as tracers (Beetem and Angelo 1964). The tracer test was conducted between wells USGS-4 and USGS-8 located about 3,100 ft west of the underground nuclear detonation, the surface projection of which is surface ground zero (SGZ) (Figure 2). Wells USGS-4 and USGS-8 are completed in the Culebra Dolomite Member of the Rustler Formation that lies above the Salado Formation. The Culebra Dolomite is a fractured carbonate aquifer of Permian age and is the most prolific aquifer near the site. For this reason, the Culebra aquifer is considered a transport pathway for tracer test and detonation-related radionuclides.

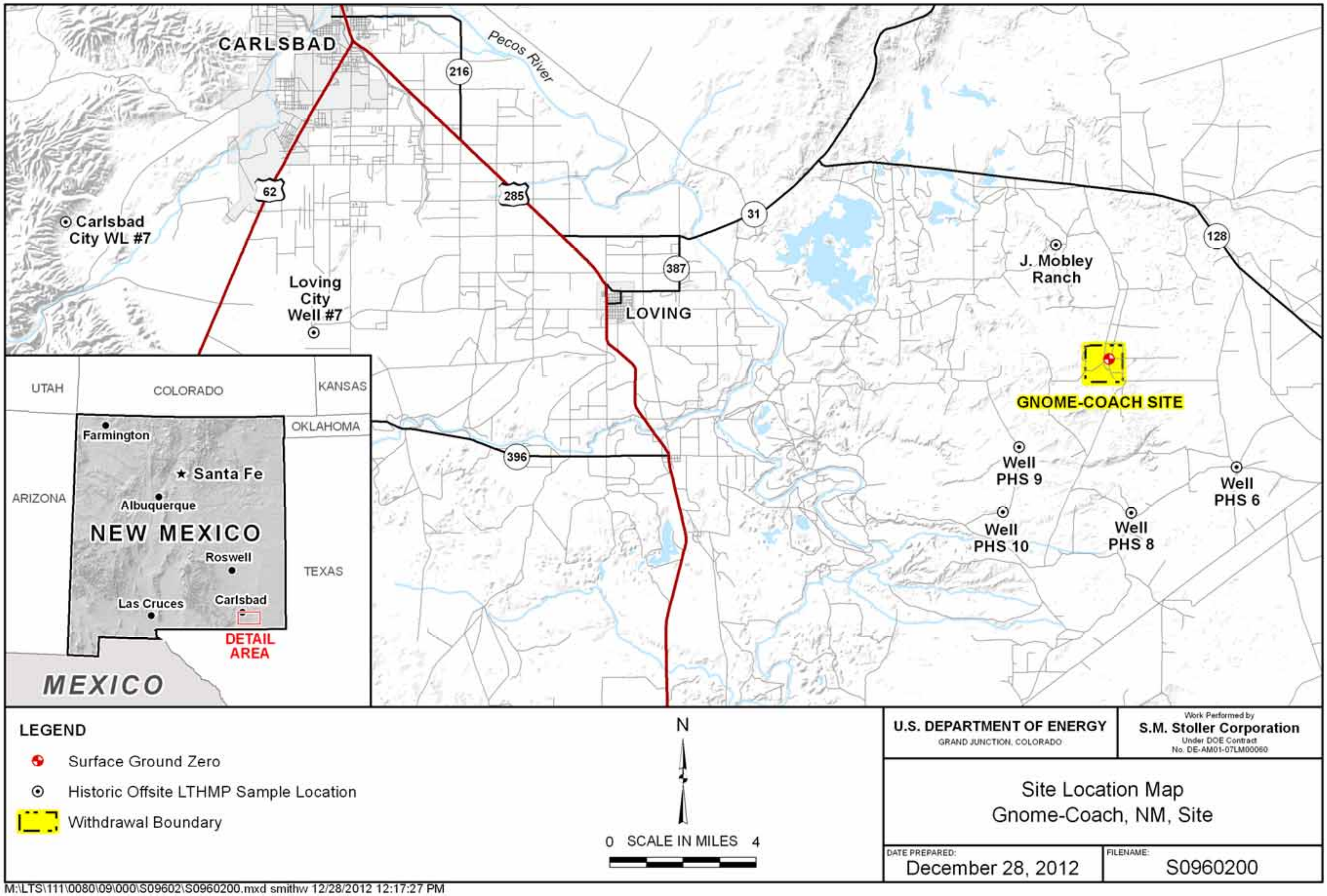

Figure 1. Site Location Map, Gnome-Coach, New Mexico, Site

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Figure 2. Site Features, Gnome-Coach, New Mexico, Site

2.1 Summary of Reclamation and Remediation Activities

Surface and subsurface contamination resulted from the underground nuclear testing, post-test drilling, and a groundwater tracer test performed at the site. Site cleanup was initiated shortly after these activities and conducted between 1968 and 1969. A second major cleanup was conducted from 1977 to 1979 (REECO 1981). In 1994, radiological contamination was identified on the surface and in the shallow subsurface (depth of 20 ft bgs) during a survey and sampling event conducted by the U.S. Environmental Protection Agency (EPA). The DOE National Nuclear Security Administration Nevada Site Office conducted a corrective action investigation to assess the extent of contamination at the site. The field investigations were performed from February through June 2002 and in May 2003. The Corrective Action Investigation Report (DOE/NNSA 2004) summarizes the results of the investigation. After discussions with the State of New Mexico, it was decided that the site would be administered under the Voluntary Remediation Program. A Completion Report, prepared in accordance with the Voluntary Remediation Program, recommended no further corrective actions, no use restrictions for the surface at the site, and the eventual goal of clean closure (DOE/NNSA 2005).

Subsurface corrective action activities have been limited and have generally consisted of annual sampling and monitoring of groundwater as part of the Long-Term Hydrologic Monitoring Program (LTHMP). EPA began the LTHMP in 1972 and conducted the sampling until 2008, when LM assumed responsibility for sampling. Since 1972, locations used for long-term sampling have changed; some locations were abandoned or replaced, and new locations have been added. Samples collected from these locations have generally been analyzed for gamma-emitting radionuclides (using high-resolution gamma spectrometry), strontium-90, and tritium (using conventional and electrolytic enrichment methods). LM evaluated the LTHMP and associated monitoring network after assuming responsibility for the sampling. The purpose of the evaluation was to determine the effectiveness of the current monitoring network and determine future monitoring at the site. The evaluation considered potential transport pathways for contaminant migration from the detonation zone and tracer test to surrounding receptors. Analytical results from more than 30 years of monitoring indicate that groundwater at sample locations outside the land-withdrawal boundary (Figure 1) were not impacted by nuclear-test-related contamination. For this reason, in 2010 locations outside the land-withdrawal were excluded from future sampling, but wells within and near the boundary continue to be monitored.

To enhance monitoring at the site, low-flow bladder pumps were installed in wells USGS-4, USGS-8, and LRL-7 in June 2008. The dedicated bladder pumps were installed to replace the previous sampling method that used a depth-specific bailer and to allow the collection of more representative samples using the low-flow sampling method. Pressure transducers were also installed in the onsite monitoring wells in 2008, 2009, and 2010 to collect hydraulic head data for evaluating groundwater flow directions. Geophysical well logging was conducted in onsite monitoring wells USGS-4, USGS-8, and USGS-1 in April 2010. The well logging was conducted to obtain borehole deviation data from wells USGS-1 and USGS-4, natural gamma data from wells USGS-4 and USGS-8, and down-hole video logs from wells USGS-4 and USGS-8. The borehole deviation data allow measured depths to be corrected to true vertical depths to support the calculation of hydraulic head at site wells that deviate from vertical. The gamma ray logs provide geologic information that can be used to correlate with other wells in the area. The video log images suggest that the well casings are generally in good condition for their age. The 2010 Groundwater Monitoring and Inspection Report (DOE 2011) summarize the well logging results.

3.0 Geology and Hydrology

The site is in the northwestern part of the Delaware Basin, a deep, oval, sedimentary basin 75 miles wide and 135 miles long in southeastern New Mexico. The geology and hydrology of this basin are well studied because of oil and gas exploration, mining, and the operation of the Waste Isolation Pilot Plant approximately 8 miles north-northeast of the site. The basin deposits generally dip gently to the east and southeast, though in places the bedding is almost flat. During the late Permian Period, a warm shallow sea in the region provided an ideal environment for reef development, which blocked seawater circulation. As the seawater began to evaporate, brines were formed, and crystalline salts precipitated and accumulated on the basin floor. As a result, the site area is underlain by several thousand feet of limestone, dolomite, gypsum, halite, anhydrite, and potassium salts (potash). The Salado Formation, in which the Gnome detonation took place, is a 2,500 ft thick bed of halite that formed during the Permian Period. The Salado Formation is virtually impermeable due to the plastic nature of the salt under pressure.

Overlying the Salado Formation are five thin-bedded members of the Rustler Formation (Figure 3). This formation includes the Culebra Dolomite Member, which is the subject of extensive study as part of the operation of the Waste Isolation Pilot Plant. Above the Culebra Dolomite is the Tamarisk Anhydrite Member, which is overlain by the Magenta Dolomite. The uppermost member of the Rustler Formation is the Forty-Niner Member, a mixture of gypsum and anhydrite. The youngest Permian sequences in the site area are the thin, red, sedimentary rocks of the Dewey Lake Redbeds Formation. At the site, about 200 ft of Permian-age anhydrites, mudstones, and dolomites separate the Culebra Dolomite from younger overlying formations.

The Culebra Dolomite is a widespread, laterally continuous, fractured carbonate aquifer that is approximately 30 ft thick and is encountered at a depth of approximately 490 ft bgs at the site. The groundwater within the Culebra generally moves through fractures and is of poor quality because of high concentrations of dissolved solids (Mercer 1983). The Culebra is the most prolific aquifer near the site, and despite the poor water quality, it is a source of water for ranchers who maintain livestock throughout the area.

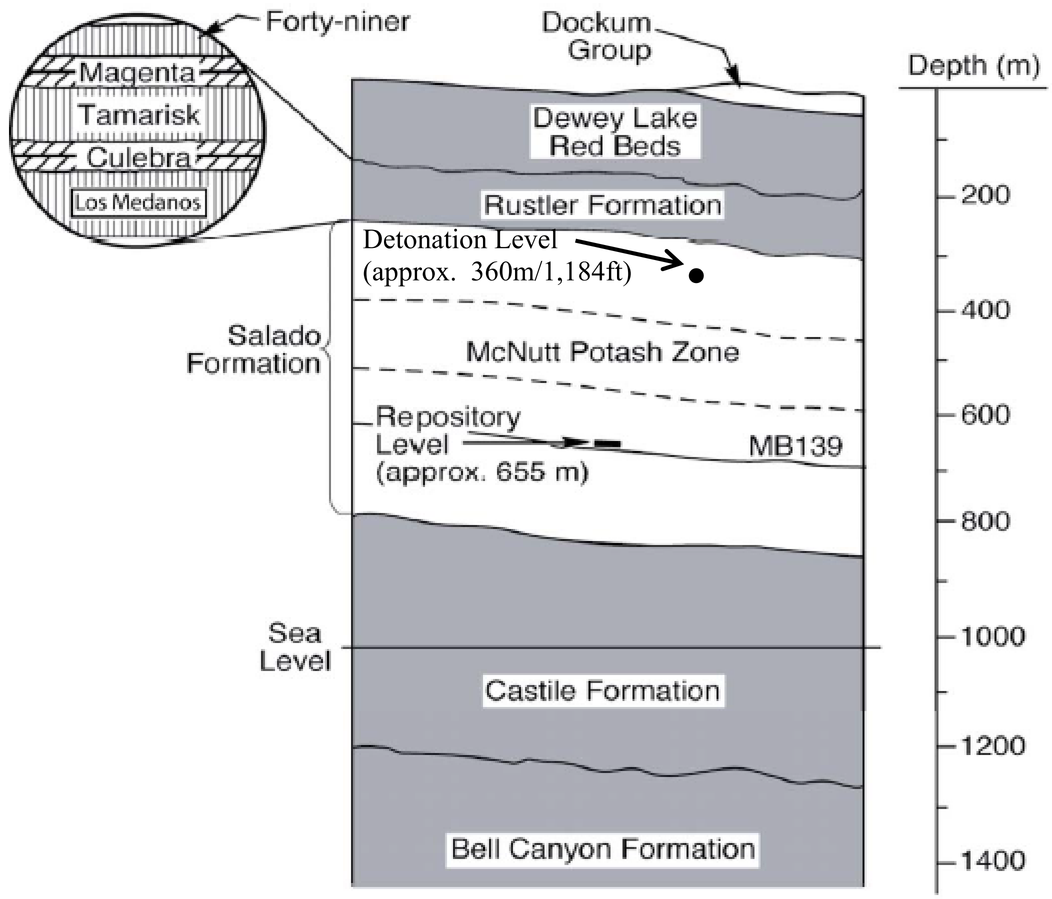

Figure 3. Stratigraphy near Gnome Site (provided by Sandia National Laboratories)

4.0 Groundwater Monitoring and Inspection Results

Groundwater monitoring and site inspection activities conducted on January 18, 2012, consisted of a site inspection, hydraulic head monitoring, and groundwater sampling. In addition to the annual groundwater monitoring and site inspection, seismic reflection data were acquired at the site from February 23 through March 10, 2012, and data from pressure transducers were downloaded in September 2012. The *Sampling and Analysis Plan for U.S. Department of Energy Office of Legacy Management Sites* (LMS/PLN/S04351) is used to guide the quality assurance/quality control of the annual sampling and monitoring program. The analytical results obtained from the annual sampling were validated in accordance with the *Environmental Procedures Catalog* (LMS/PRO/S04325), "Standard Practice for Validation of Laboratory Data." All samples were analyzed using accepted procedures that were based on the specified methods. The laboratory radiochemical minimum detectable concentration reported with these data is an estimate of the predicted detection capability of a given analytical procedure, not an absolute concentration that can or cannot be detected. A copy of the Data Validation Package is maintained in the LM records and is available upon request.

4.1 Site Inspection Results

The inspection included evaluating roads and monitoring well heads and inspecting the monument at SGZ for any signs of damage, natural deterioration from weather, or vandalism. All roads, well heads, and the monument were in good condition at the time of the inspection.

Well head boxes were installed at wells USGS-4, USGS-8, and LRL-7 in January and March to improve well head security. Water access tubes were installed in wells USGS-4 and USGS-8 to facilitate water level measurement and transducer installation. Installation of the water access tubes established new measuring points on the top of casing for measuring depth to groundwater in the wells. In September 2012, LM was informed that a water truck had driven over the USGS-1 well head the previous April. The impact had damaged the well head and caused the water access tube and transducer to drop to the bottom of the well. The well head has been repaired, but the water access tube with transducer remains in the well. As a result, no transducer data are available from this well through September 2012. LM is making arrangements to recover the equipment and install a new water access tube as part of the next annual site inspection. The next annual site inspection will also include a survey of the water access tube top of casings so depth to groundwater measurements can be converted to elevations. Photos of the well head boxes and well head modification are provided in Appendix A.

4.2 Hydraulic Head Monitoring and Results

Heads were recorded every 3 hours by pressure transducers in site wells (USGS-1, USGS-4, USGS-8, LRL-7, and DD-1). The transducer data were downloaded, and water levels were measured manually in all wells except DD-1 as part of the annual monitoring event on January 18, 2012. A water level was later measured in DD-1 on March 7, 2012. The manual water level measurements were collected using a water level tape prior to activities that would disturb ambient water level conditions. The transducer data in wells USGS-4, USGS-8, and LRL-7 were downloaded again in September 2012. The transducer in well LRL-7 failed in mid-June, so no data are available from mid-June through September 2012 for this well. Transducer data in well DD-1 were not downloaded in September because the well is completed in the detonation cavity and access is restricted. Transducer data in well USGS-1 were also not downloaded in September because the well had been damaged and the transducer was no longer accessible at the well head. Subsequently, data are not currently available from wells USGS-1 and DD-1 for the latter portion of the monitoring period that ended in September 2012. The manual water level measurements were used to convert the transducer data to groundwater elevations. Transducer data were corrected for the different specific gravity of water for each screened unit. The specific gravity of water in Culebra screened wells is about 1.0025. The specific gravity of water from Salado screened wells is about 1.15. Water elevations were not converted to a freshwater equivalent groundwater elevation. Table 1 presents the water level data and measured groundwater elevations obtained in 2012, along with the zone of completion and the hydrostratigraphic unit monitored for the wells.

Table 1. Gnome-Coach Site Water Levels

Well	Date	DTW (ft)[a]	TOC Elevation (ft amsl)	TSZ Elevation (ft amsl)	BSZ Elevation (ft amsl)	Formation/Unit Monitored	Groundwater Elevation (ft amsl)
USGS-1[c]	1/18/2012	434.10	3,425.78	2,907.78[b]	2,875.78[b]	Culebra Dolomite	2,991.77[b]
USGS-4	1/18/2012	426.66	3,415.25	2,943.22[b]	2,909.70[b]	Culebra Dolomite	2,993.42[b]
USGS-8	1/18/2012	419.79	3,412.96	2,949.96[b]	2,917.96[b]	Culebra Dolomite	2,993.17[b]
LRL-7	1/18/2012	469.49	3,442.42	2,654.42[a]	2,128.42[a]	Salado Formation	2,972.93[a]
DD-1	3/07/2012	1,023.50	3,398.18	2,261.18[a]	NM	Salado Formation	2,374.68[a]

BSZ = bottom of screen zone, uncased/open interval, or perforated interval in feet above mean sea level
DTW = depth to water (all measurements obtained from north top of casing)
NM = not measured or unknown
TOC = top of casing elevation in feet above mean sea level
TSZ = top of screen zone, uncased/open interval, or perforated interval in feet above mean sea level
amsl = above mean sea level
[a] Depth to water has not been corrected for true vertical depth and elevations for LRL-7 and DD-1 have not been corrected for true vertical depth because borehole deviation corrections are not available for these wells.
[b] Elevation has been corrected for true vertical depth (at the water level depth, the deviation correction for USGS-1 is 0.09 ft; USGS-4 is 4.83 ft; USGS-8 did not deviate from vertical, so no correction is required).
[c] Well USGS-1 has a dedicated submersible pump that was operating at the time of the measurement.

The hydraulic head data are shown in Figure 4 and Figure 5. The hydrographs are grouped according to each well's open interval and formation monitored. Head data collected using a water level tape appear as individual symbols, and data collected with transducers appear as lines. Figure 4 shows the hydrographs for the wells (USGS-1, USGS-4, and USGS-8) completed in the Culebra Dolomite. Well USGS-1 provides water for livestock belonging to area ranchers, and a dedicated submersible pump cycles on and off to maintain a constant volume in a nearby water tank. Data from well USGS-1 are only available for a portion of this monitoring period, but historical data indicate that water levels in this well recover approximately 2 ft when the dedicated pump in the well cycles off (Figure 4). As a result of the limited data set, it is difficult to make a direct correlation between the pumping in well USGS-1 to changes in water levels in wells USGS-4 and USGS-8 for this monitoring period. Figure 5 shows the hydrographs for wells (LRL-7 and DD-1) completed in the Salado Formation. It was determined that the manual water level collected from LRL-7 in January 2009 and previously used to convert the transducer data to elevations did not correspond to the actual water level when the transducer was installed. The manual water levels collected in January 2011 and 2012 support this determination and were used to convert the transducer data to elevations. Hydraulic head data indicate that the water level in well LRL-7 does not fully recover from annual sampling events. Water levels in well DD-1 abruptly stopped rising in June 2011, and it is currently uncertain if the data from DD-1 are correct or the result of a transducer malfunction. Attempts were made in January and March 2012 to verify these data by raising the transducer in measured increments to evaluate if recorded pressure responses were consistent with the incremental raising of the transducer. At this time it appears that the transducer is functioning correctly. Because of the known contamination, the transducer was not removed from the well. Also, hydraulic head data from wells USGS-1, USGS-4, and USGS-8 have been corrected to true vertical depth. For reference, the borehole deviation data obtained from well USGS-4 requires a correction of 4.83 ft to obtain true vertical depth (DOE 2011). Borehole deviation data are currently not available for wells DD-1 and LRL-7, so groundwater elevations depicted in Figure 5 are approximate.

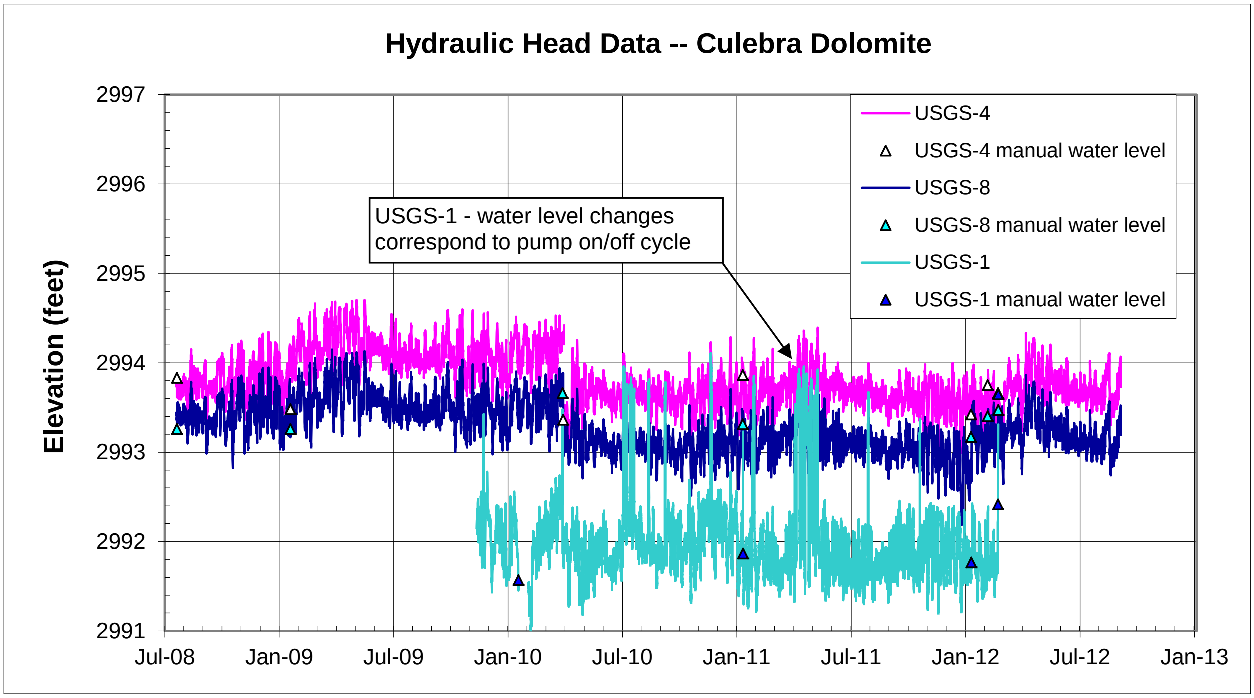

Figure 4. Hydrograph Showing Water Elevations in Wells USGS-1, USGS-4, and USGS-8

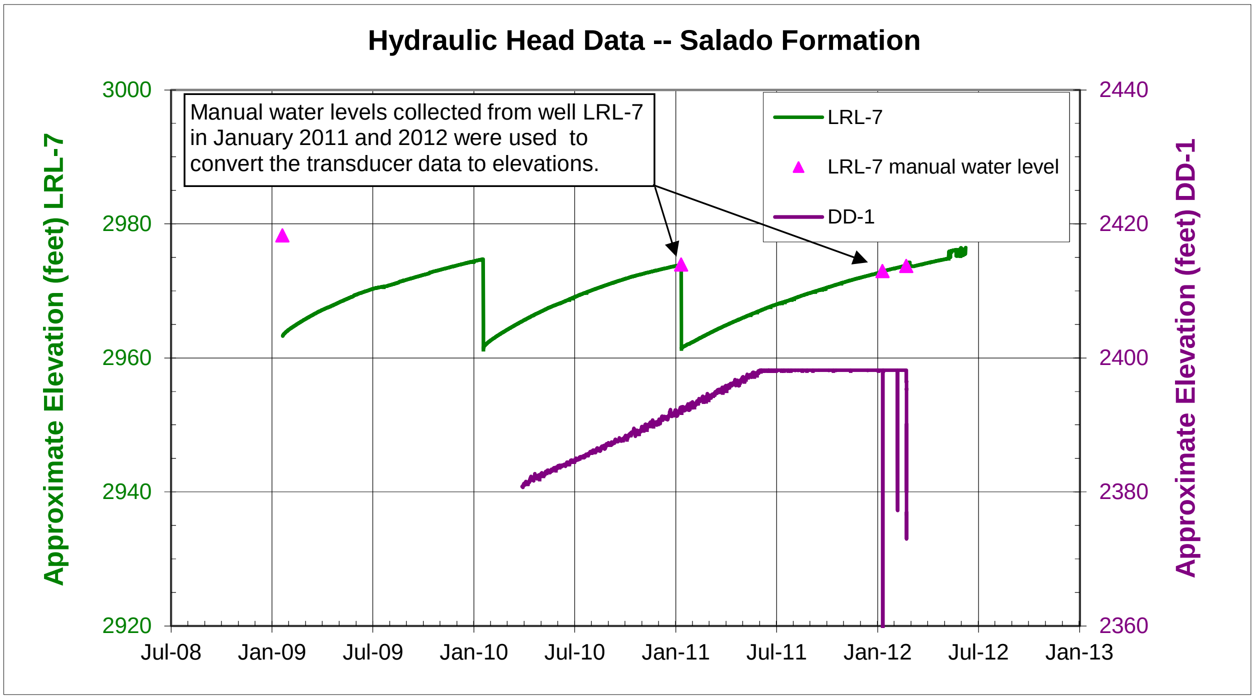

Figure 5. Hydrograph Showing Water Elevations in Wells DD-1 and LRL-7

4.3 Groundwater Sampling and Results

Groundwater samples were collected from wells USGS-1, USGS-4, and USGS-8 on January 18, 2012. A sample was not collected from well LRL-7 during this monitoring event to allow water levels at this location to continue to recover from the previous year's sampling event. A sample was also not collected from well DD-1 because the presence of contamination in this well is well documented. Monitoring wells USGS-4 and USGS-8 were sampled using dedicated low-flow submersible bladder pumps. The tubing inlets of the bladder pumps are located in the screened or open interval to allow water to be collected directly from the adjacent geologic formation. The sample from well USGS-1 was collected as a grab sample because the pump was operating to replace water in the nearby stock tank at the time of the sampling. Samples were analyzed for gamma-emitting radionuclides (using high-resolution gamma spectrometry), strontium-90, and tritium (using conventional methods). An additional sample was collected from well USGS-1 for tritium analysis using the electrolytic enrichment method.

Table 2 presents a summary of analytical results from the sampling event in 2012 along with the results from 2008 through 2011 for comparison. LM has performed the sampling at the site since 2008. Prior to 2008, EPA had conducted the sampling and, until the 2012 sampling event, had also analyzed the samples. Samples collected during this monitoring event were analyzed by GEL Laboratories in Charleston, South Carolina. Analytical results obtained from the 2012 monitoring event were generally consistent with previous analytical results. The exceptions are the results for strontium-90 in samples from wells USGS-4 and USGS-8. Concentrations of strontium-90 in these samples decreased by a factor of more than 2.5 last year's results (Table 2). It is uncertain if the decrease in strontium-90 in these wells is attributable to the change in laboratories, a 1-year anomaly, or a developing trend. The radionuclide concentrations in wells USGS-4 and USGS-8 are the result of radionuclides injected during the tracer test in 1963. Radionuclides above the laboratory minimum detectable concentration were not detected in the samples from well USGS-1 (Table 2).

Charts 1 through 7 in Appendix B show temporal plots of radionuclide concentrations (1972 through 2012) in samples collected at wells LRL-7, USGS-4, and USGS-8. Concentrations are plotted on a semilogarithmic scale. All sample results, including nondetects, are plotted. As indicated in the charts, many results from sampling events before the late 1980s had no reported detection limit. For interpretation purposes, relatively high concentrations (i.e., concentrations significantly higher than detection limits associated with subsequent sampling) should be considered detections. The increases in tritium concentrations in samples collected from well LRL-7 (Chart 1) and cesium-137 concentrations in samples collected from wells USGS-8 and LRL-7 (Chart 4 and Chart 6) after the 2007 sampling event are attributed to changes in the sampling method. Prior to 2008, EPA collected samples using a depth-specific bailer, and after 2007, LM collected samples from dedicated bladder pumps using the low-flow sampling method. Tritium concentrations in samples collected from well USGS-4 (Chart 1) also appear to be decreasing at a rate that is greater than the natural decay rate for tritium.

Table 2. Analytical Results 2008 through 2012

Sample Location	Collection Date	Tritium (pCi/L)	Enriched Tritium (pCi/L)	Cesium-137 (pCi/L)	Strontium-90 (pCi/L)	Formation/Unit Monitored
USGS-1	7/30/2008	<169	NA	<5.0	NA	Culebra Dolomite
	1/27/2009	<154	NA	<4.94	<1.8	
	1/26/2010	<146	7.6	<2.1	<0.89	
	1/26/2010 [a]	<146	<3.4	<1.4	<1.9	
	1/19/2011	<150	NA	<2.2	<3.6	
	1/19/2011 [a]	<150	NA	<2.4	<1.1	
	1/18/2012	<240	<2.33	<5.69	<0.728	
	1/18/2012 [a]	<243	NA	<6.82	<0.794	
USGS-4	7/30/2008	22,300	NA	<4.59	NA	Culebra Dolomite
	1/27/2009	16,800	NA	<4.99	2,980	
	1/26/2010	13,200	NA	<1.4	2,540	
	1/19/2011	11,300	NA	<2.4	2,650	
	1/18/2012	9,110	NA	<5.62	884	
USGS-8	7/30/2008	30,000	NA	154	NA	Culebra Dolomite
	1/27/2009	28,800	NA	163	3,440	
	1/27/2010	25,500	NA	181	3,320	
	1/19/2011	21,200	NA	150	3,650	
	1/18/2012	21,700	NA	154	1,400	
LRL-7	7/30/2008	4,070	NA	126	NA	Salado Formation
	1/28/2009	4,870	NA	139	<24	
	1/26/2010	4,350	NA	129	<33	
	1/19/2011	3,910	NA	134	<29	
	1/18/2012	NA	NA	NA	NA	

[a] = Indicates a field duplicate sample
NA = not analyzed; pCi/L = picocuries per liter

4.4 Seismic Data Acquisition and Results

A seismic survey was conducted at the Gnome-Coach site from February 23 to March 10, 2011. Seven seismic reflection profiles (Figure 6) totaling approximately 13.9 miles were acquired to assist in the interpretation of subsurface hydrogeology, development of conceptual site model, and locating future monitoring wells. The survey was designed to image the upper few thousand feet of the section, which includes the tracer test (at a depth of about 450 ft bgs at wells USGS-4 and USGS-8) and the detonation (at a depth 1,184 ft bgs). A check shot survey was acquired in well USGS-4 to calibrate the seismic profiles to the subsurface lithology. Reflections that correlate to the top of the Gatuna Formation, the top of the Rustler Formation, the top of the Salado Formation, and the top of the Castile Formation were present on most of the seismic profiles. Significant features identified that would influence groundwater flow were areas of solution and collapse in the evaporites overlying the Salado Formation (Rustler and Culebra Formations) and possible faults that cross the site. Identification of these features is interpretive and generally based on the experience of the geophysicists. The seismic data will continue to be evaluated as new information becomes available. A comprehensive description of the seismic survey is included in Appendix C.

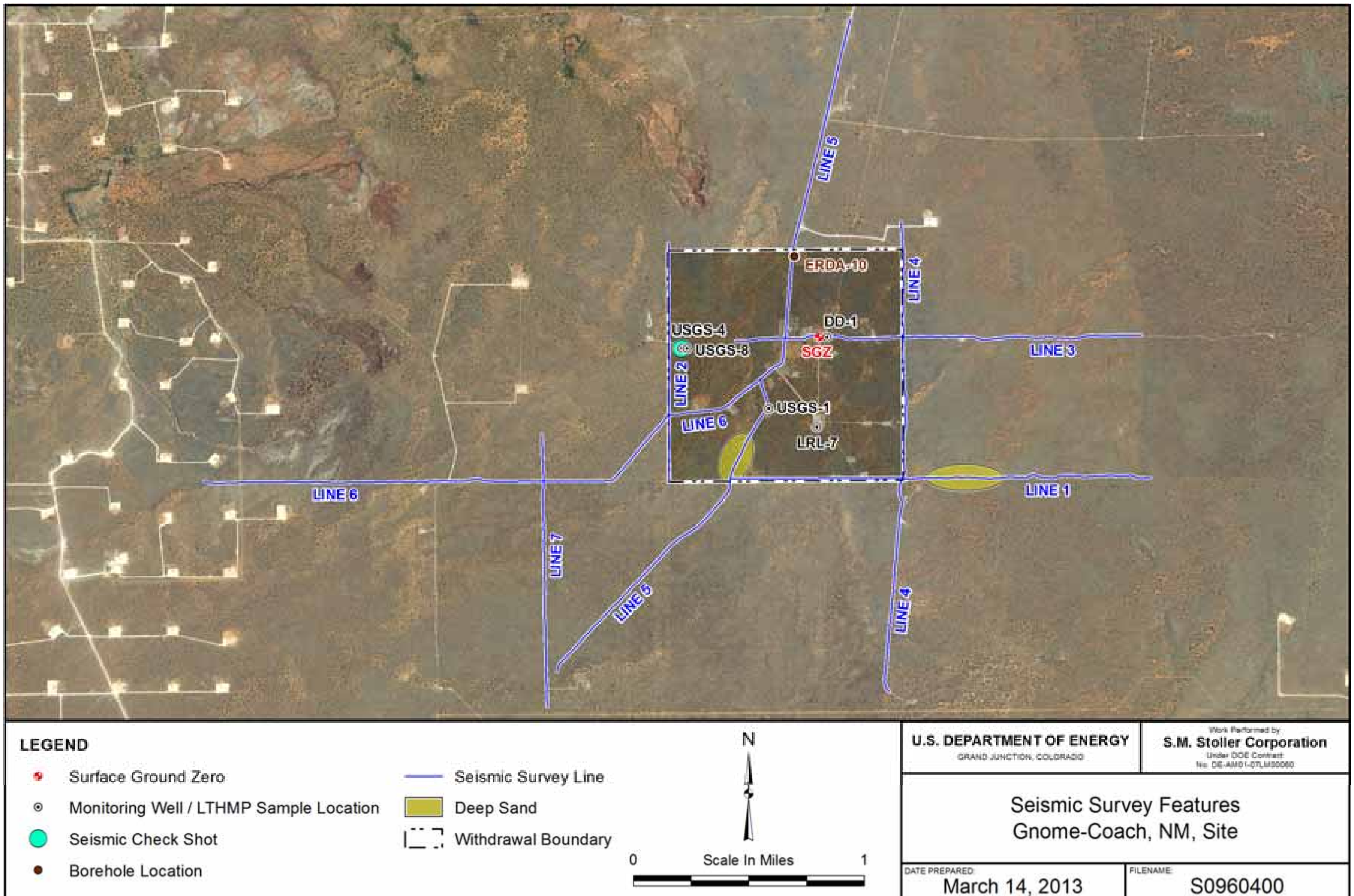

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Figure 6. Seismic Survey Features, Gnome-Coach, New Mexico, Site

5.0 Conclusions

The annual site inspection and sampling event were conducted on January 18, 2012. Analytical results obtained from this sampling event indicate that concentrations of tritium, strontium-90, and cesium-137 were generally consistent with historical sampling results. The exceptions are the concentrations of strontium-90 in samples from wells USGS-4 and USGS-8, which were more than 2.5 times lower than last year's results. It is uncertain if the decrease in strontium-90 in these wells is attributable to the change in laboratories, a 1-year anomaly, or a developing trend. Water levels in wells USGS-4 and USGS-8 respond to the on/off cycling of the water supply pumping from well USGS-1. Well LRL-7 was not sampled in January, and water levels were still increasing when the transducer data were downloaded in September.

A seismic reflection survey was also conducted this year. The survey acquired approximately 13.9 miles of seismic reflection data along 7 profiles on and near the site. These activities were conducted from February 23 through March 10, 2012. The site roads, monitoring well heads, and the monument at surface ground zero were in good condition at the time of the site inspection. However, it was later reported in September 2012 that the USGS-1 well head had been damaged by a water truck in April 2012. The well head has been repaired, but the water access tube with transducer currently remains in the well. As a result, no transducer data are available from this well through September 2012.

6.0 References

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Appendix A

Photos of the Well Box

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Photo 1. LRL-7 Well Box

Photo 2. USGS-8 Well Box and Modified Well Head

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Appendix B

Well Concentration Plots

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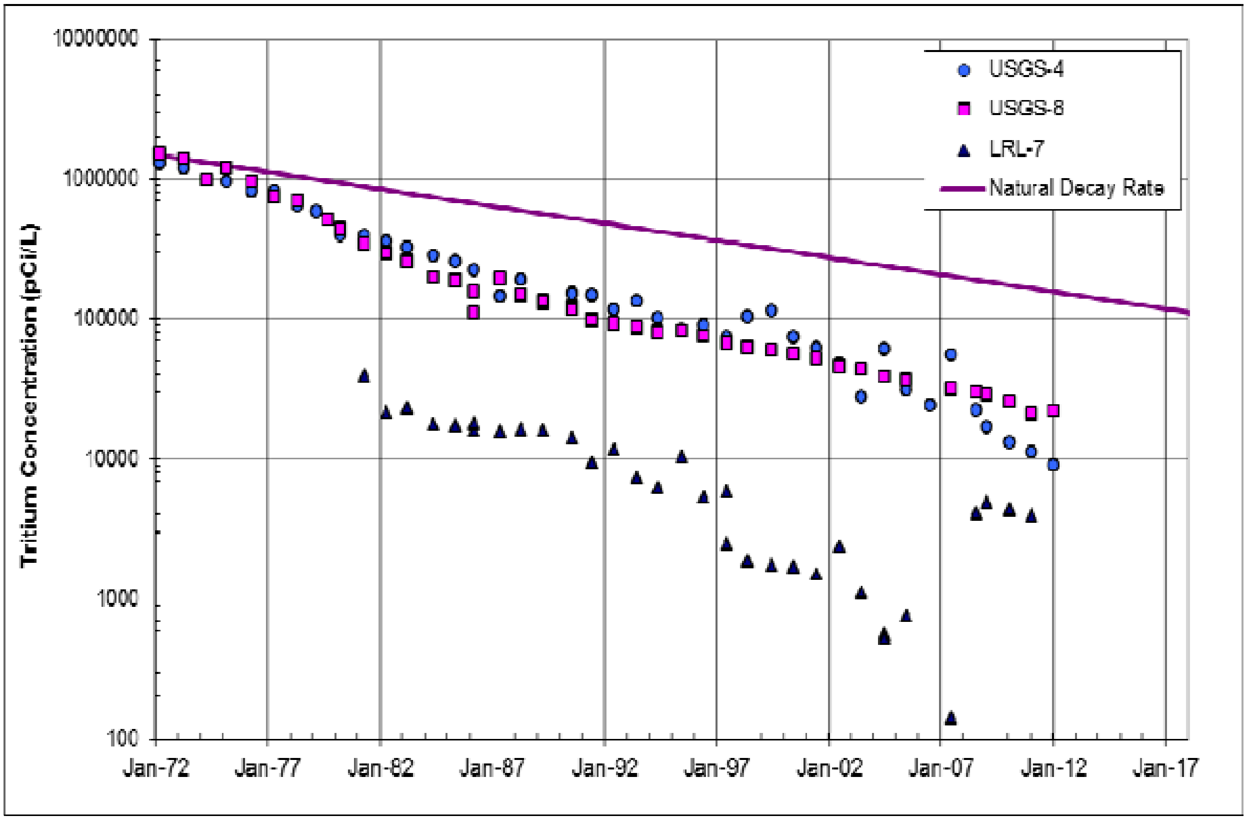

Chart 1. Tritium Concentrations at Wells USGS-4, USGS-8, and LRL-7

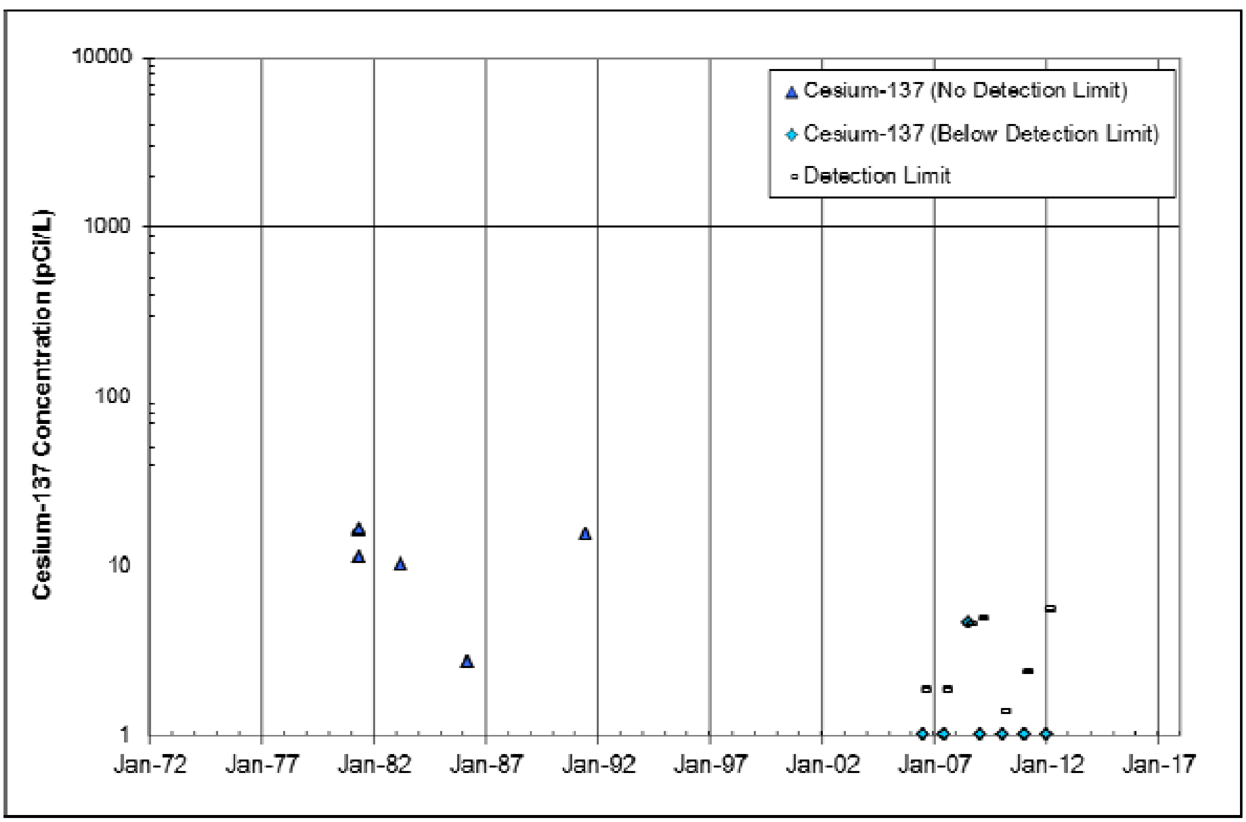

Chart 2. Cesium-137 Concentrations at Well USGS-4

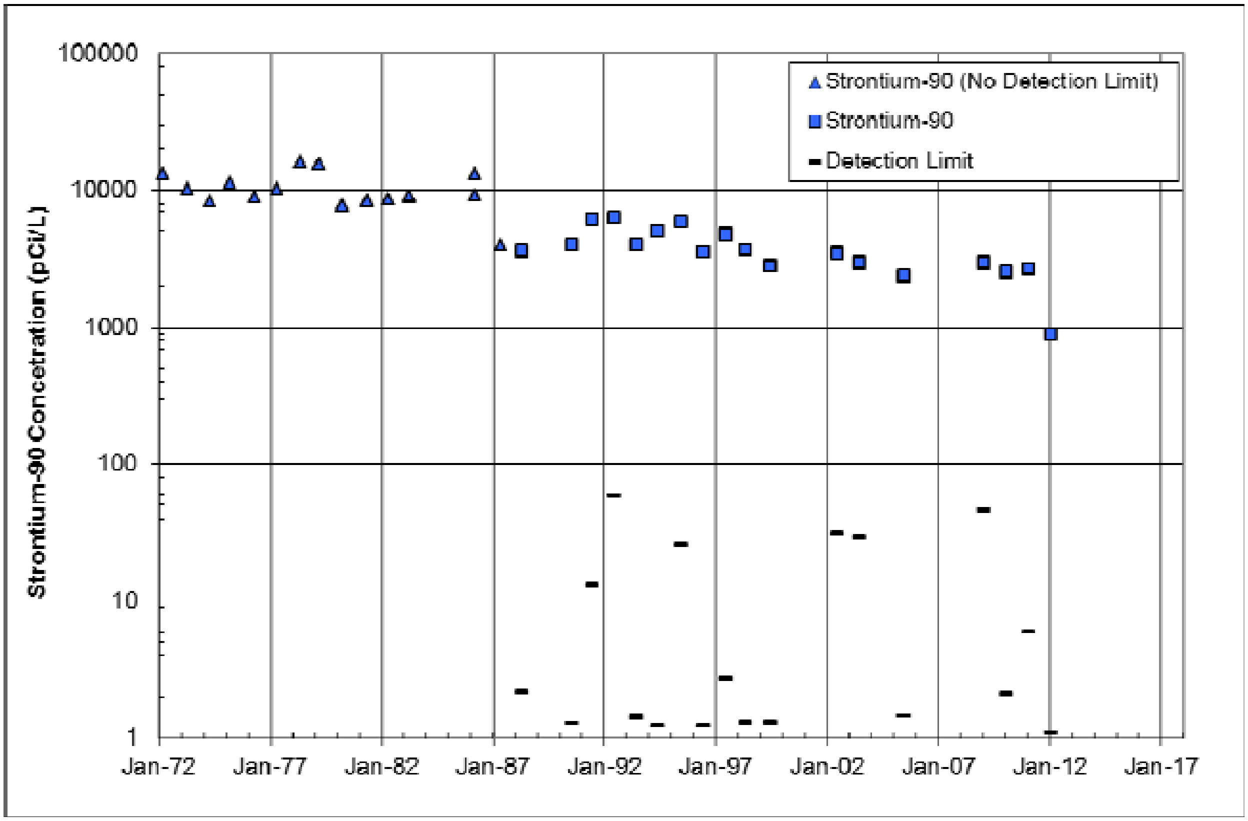

Chart 3. Strontium-90 Concentrations at Well USGS-4

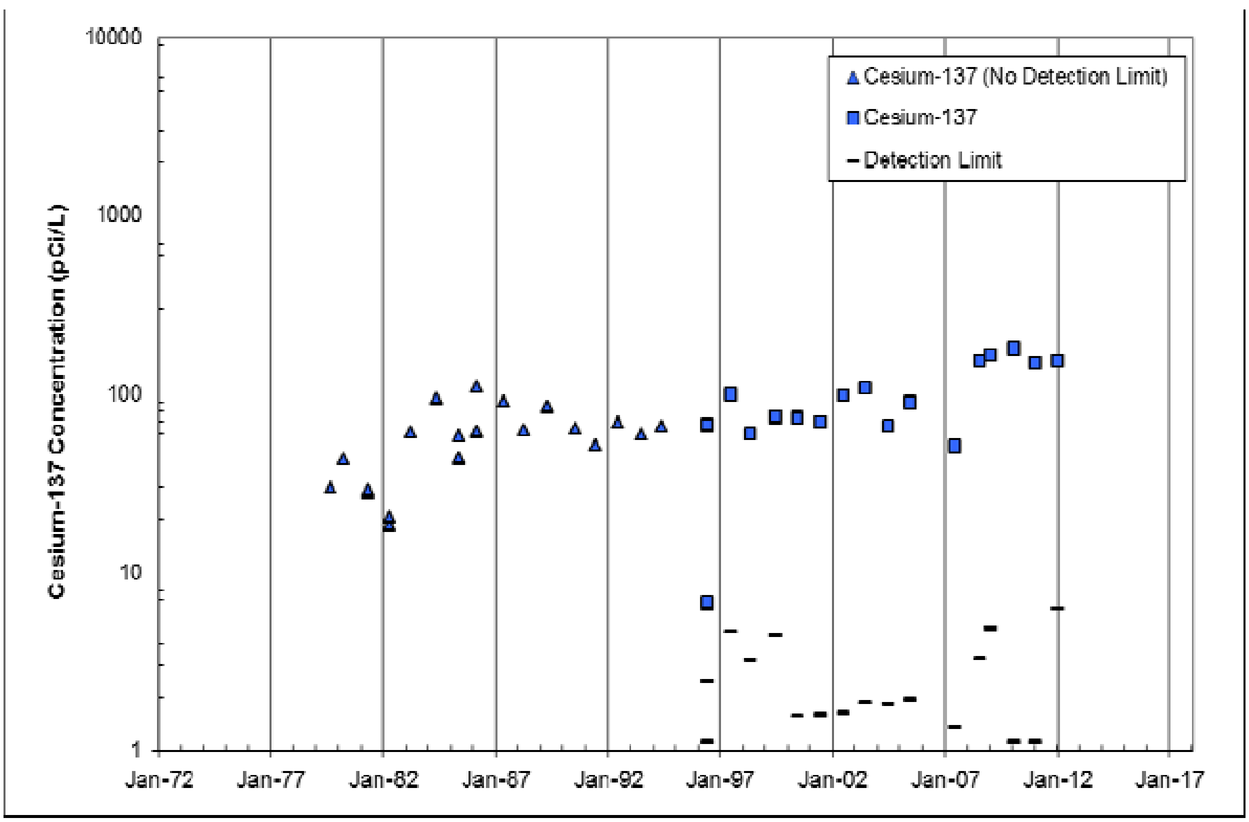

Chart 4. Cesium-137 Concentrations at Well USGS-8

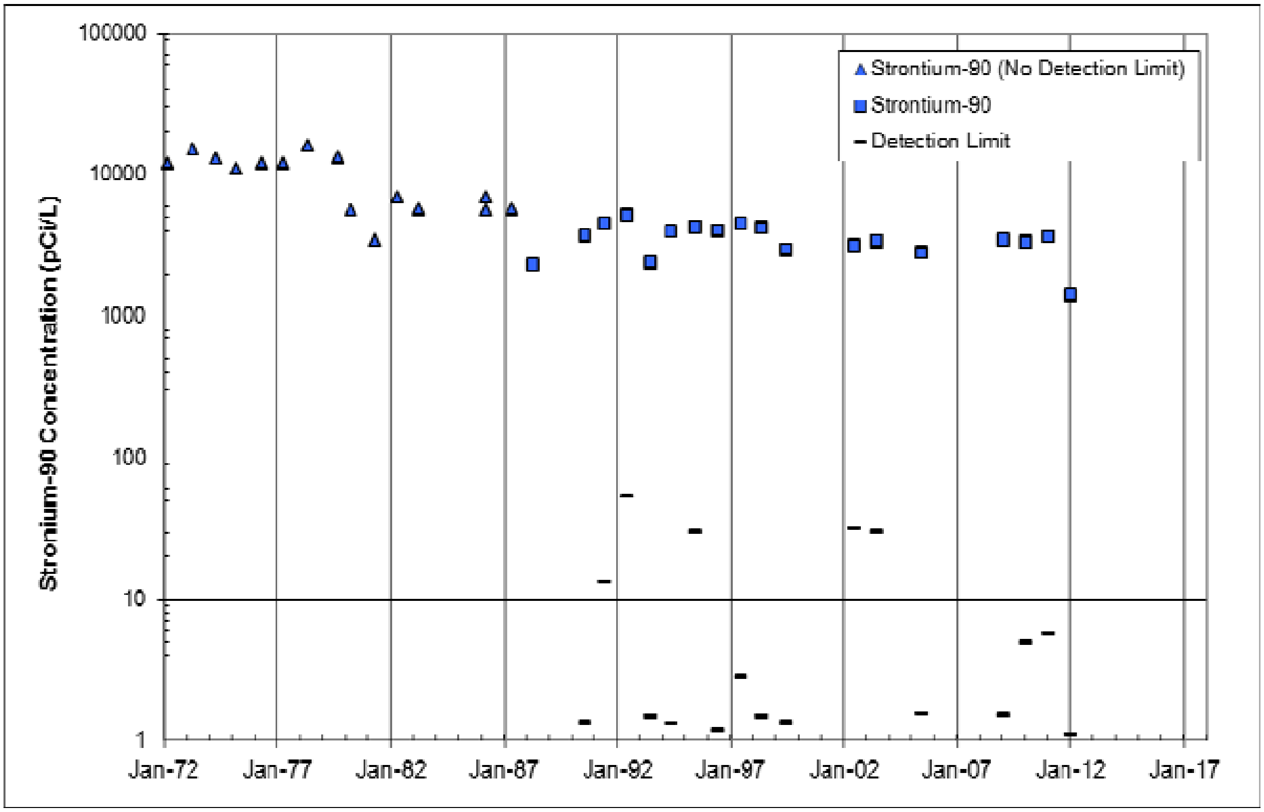

Chart 5. Strontium-90 Concentration at Well USGS-8

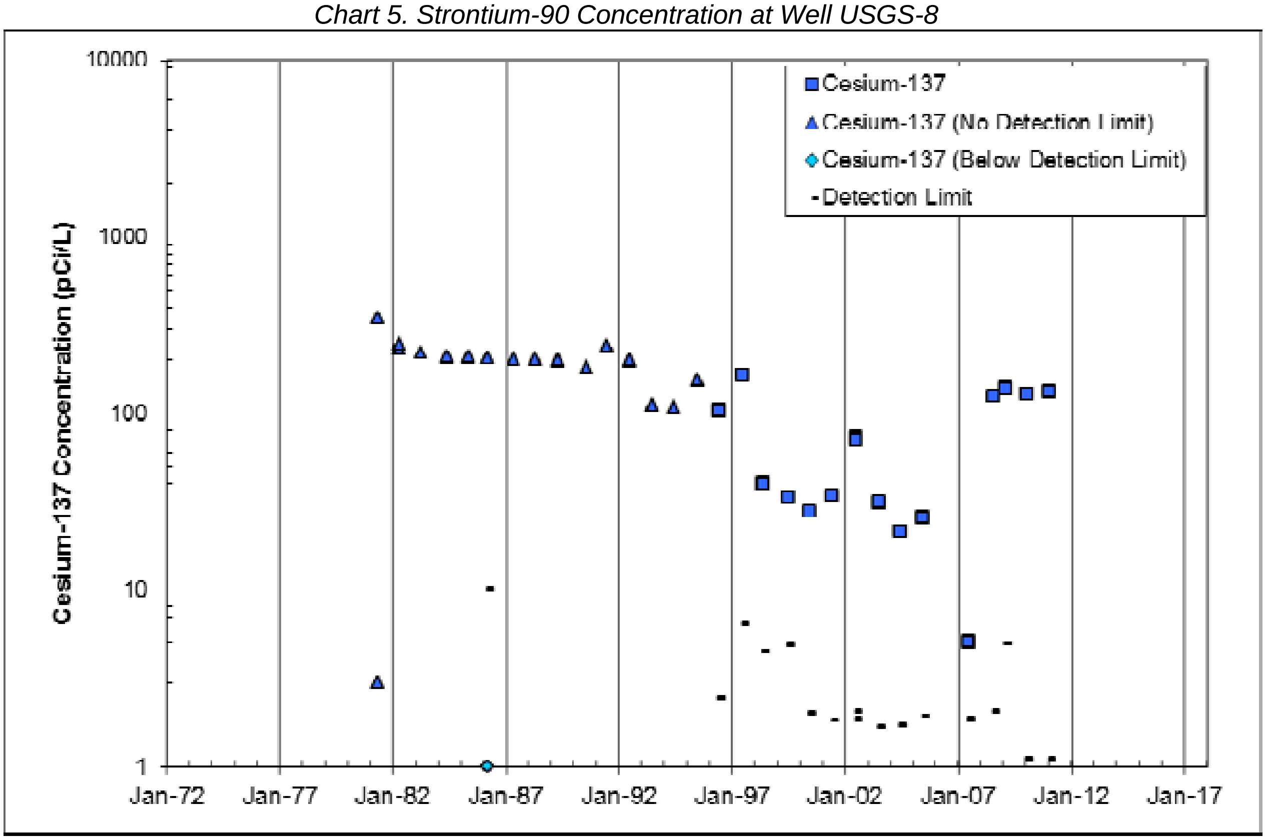

Chart 6. Cesium-137 Concentration at Well LRL-7

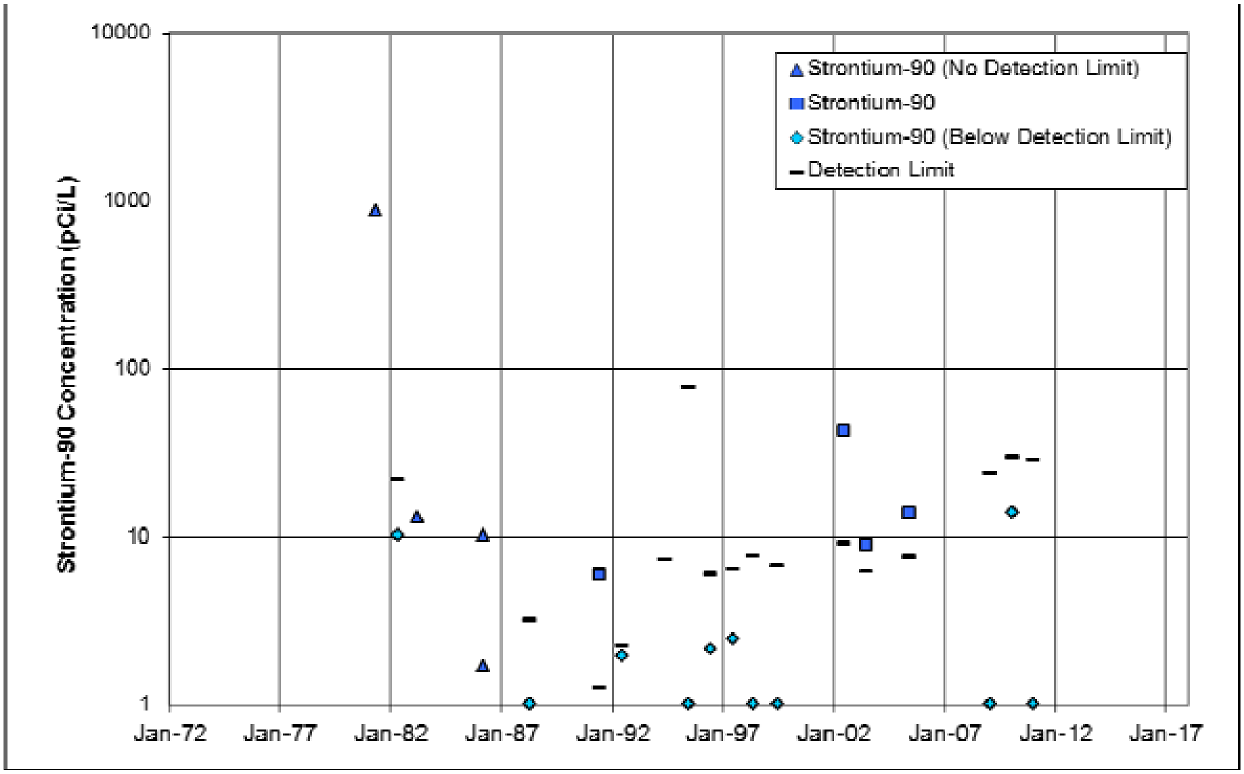

Chart 7. Strontium-90 Concentrations at Well LRL-7

Appendix C

Seismic Survey Report

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Seismic Reflection Imaging at the Gnome-Coach Site, New Mexico—Technical Report

Submitted to the S.M. Stoller Corp.

31 October 2012

DRAFT

Contact: Rick Findlay/Rex Hodges

Address: 2597 Legacy Way

Grand Junction, CO 81503

(970) 248-6714

Subcontract to the U.S. Department of Energy
Office of Legacy Management

Lee M. Liberty

Center for Geophysical Investigation of the Shallow Subsurface (CGISS)

Department of Geosciences

Boise State University

Boise, Id. 83725-1536

lliberty@boisestate.edu

208-426-1166 (office)

Setting

The Gnome-Coach site is located in the northwest portion of the Delaware Basin, southeastern New Mexico (Newell et al. 1953; Figure 1). The elevation at the site is approximately 3,400 feet (ft) above mean sea level, and topographic relief along the length of the seismic profiles (~3 square miles) is approximately 250 ft. The geology in the upper few thousand feet consists mostly of late Permian and younger sandstones, siltstones, evaporites, and carbonates that lie beneath a thin layer of late Quaternary alluvium, windblown sand, caliche, and playa lake deposits (Figures 1 and 2; Cooper 1960). The 40–80 ft thick Pleistocene Gatuna sandstone and conglomerate lie beneath and, in places, are exposed at the Gnome-Coach site. The Permo-Triassic Dewey Lake siltstone, shale, and sandstone unit and the Rustler sandstone, silt, and dolomite unit lie in the upper 1,000 ft, unconformably below the Gatuna Formation, and above the Gnome blast depth. The top of the Rustler Formation is about 200–300 ft below ground surface at the site and contains undulating layer boundaries that result from solution and collapse that have affected the formation. Not all members of the Rustler Formation are present in each of the Gnome-Coach area wells.

The nuclear device was detonated at a depth of 1,184 ft below surface ground zero (SGZ) in the Salado Formation, an approximately 1,600 ft thick bedded salt deposit. This formation lies immediately below the Rustler Formation, and the blast depth was 525 ft below the top of the Salado. Immediately below the Salado Formation, evaporites of the Castile Formation and deep-water deposits of the Bell Canyon Formation are targets of oil and gas exploration. Although these units are below target depths of this study, reflections from them provide a regional framework for structural and stratigraphic controls for the Delaware Basin and can also be used to confirm that seismic energy has propagated through the target zone.

The Culebra Dolomite Member of the Rustler Formation, a fractured carbonate aquifer, is considered the most prolific aquifer near the site. The 25–50 ft thick Culebra Dolomite appears both massive and brecciated, contains both partially filled and open cavities, and is mapped at depths of 375–550 ft below land surface (Gard 1968). The U.S. Geological Survey performed a tracer test in the Culebra aquifer in 1963 to determine travel velocities of the unit. Radionuclides (tritium, cesium-137, strontium-90, and iodine-131) were injected into well USGS-8 and extracted from well USGS-4 (Beetem and Angelo 1964). The Culebra is at a depth of about 470 ft at these wells. Radionuclides not recovered remain as a contaminant source in the subsurface; the highest concentrations are in well USGS-8.

Approximately 14 miles of seismic reflection data were acquired along seven seismic profiles at the Gnome-Coach site. Additionally, one downhole seismic survey was collected in well USGS-4 (Figure 2). The objective was to assess the integrity of the Culebra and to map stratigraphy in the upper few thousand feet. This will help identify potential transport pathways for any tracer test radionuclides or detonation-related radionuclides that might be released to groundwater. The Culebra is confined above by high seismic velocity anhydrite and low seismic velocity gypsum of the Tamarisk Member and below by clay of the Los Medanos Member of the Rustler Formation.

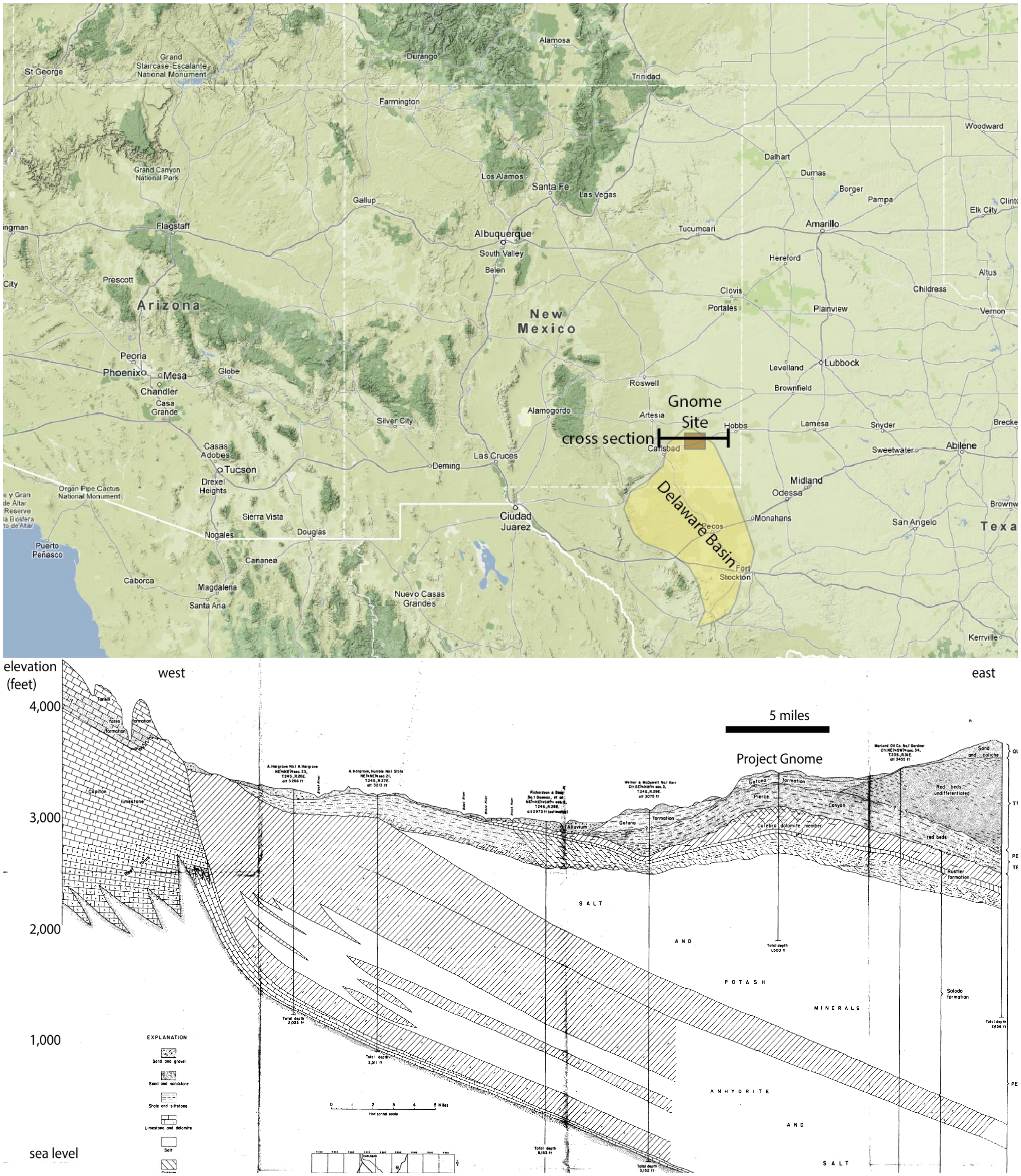
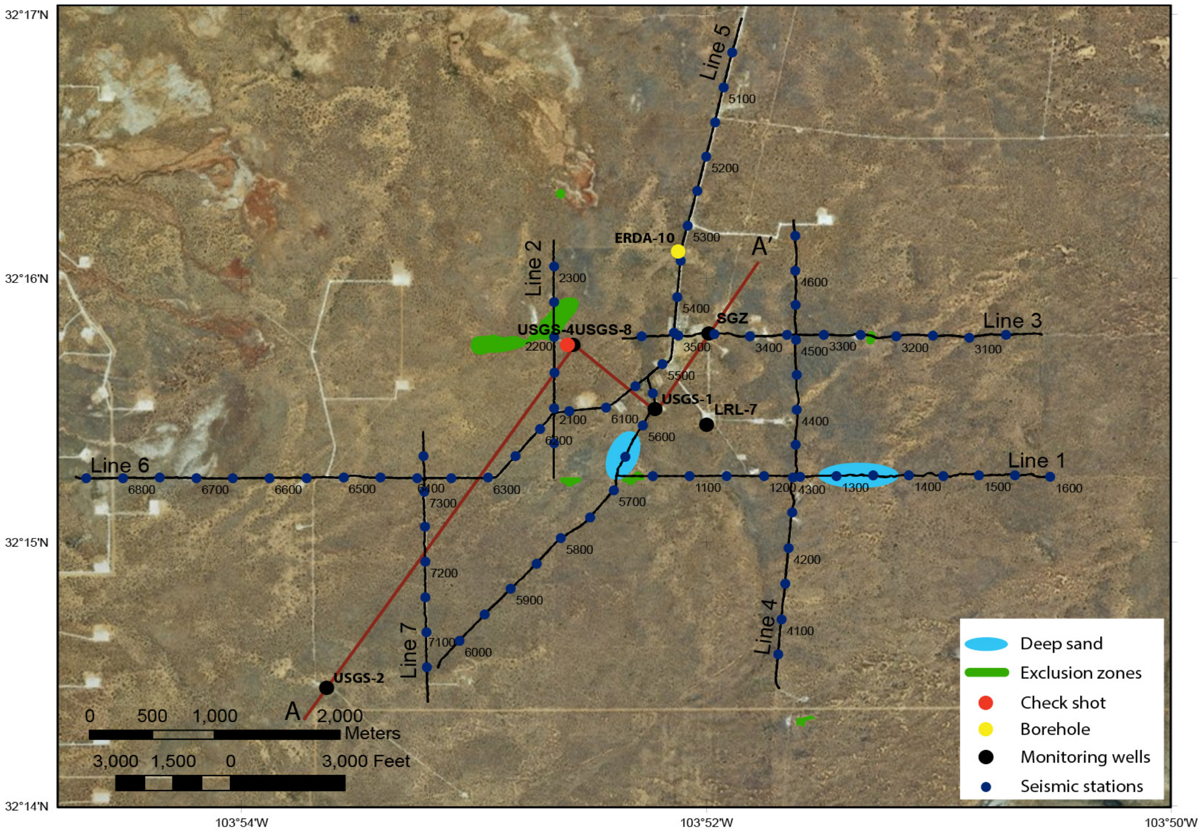


Figure 1. (top) Regional map for the Gnome-Coach site, located within the Delaware Basin, southeast New Mexico. (bottom) Cross section from Carlsbad and through the Gnome-Coach site showing regional stratigraphy (from Cooper 1960).



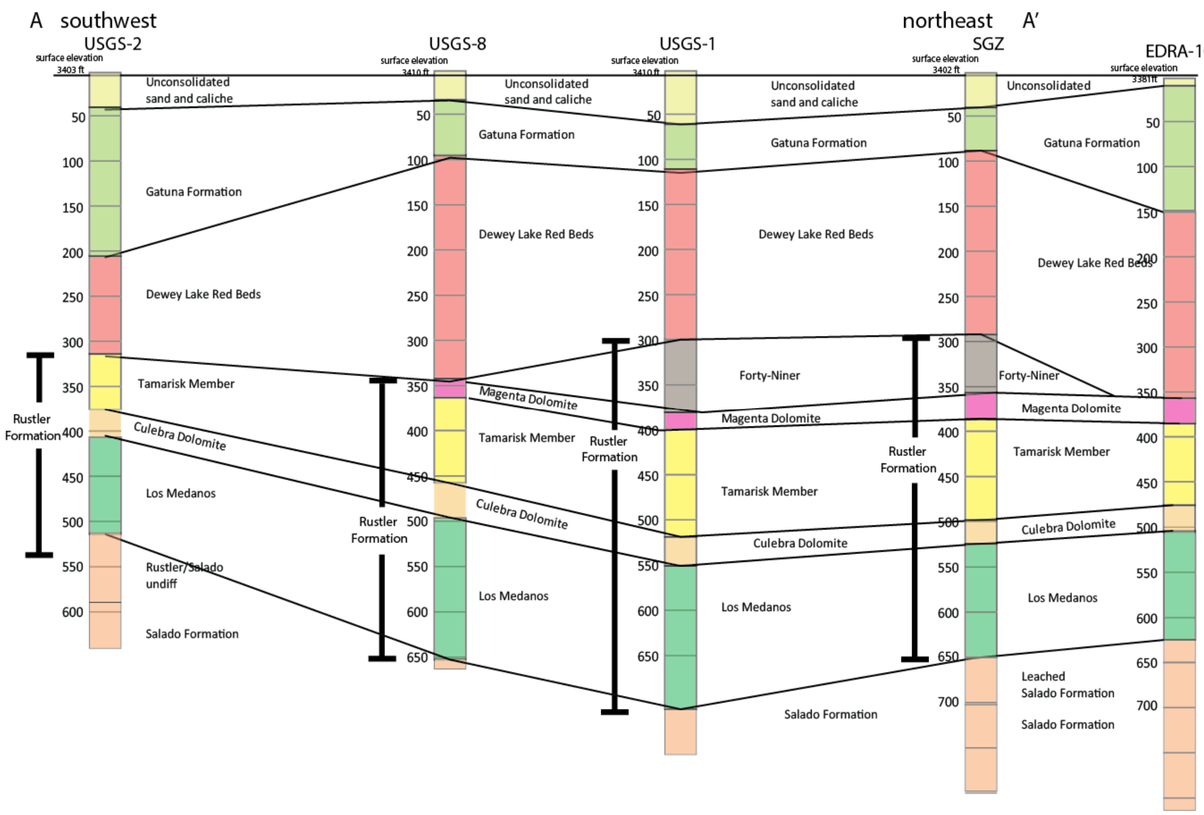


Figure 2. (top) Project Gnome site map with seismic profile locations, SGZ well, and monitoring well/borehole locations. VSP check-shot survey was acquired in well USGS-4. Figure 2. (bottom) Simplified cross section through 4 wells. Borehole ERDA-10 is projected onto the line of section.

Seismic Methods

Vertical seismic profile survey

We acquired a check-shot or vertical seismic profile (VSP) survey in well USGS-4 (Figure 2). This technique uses a downhole geophone coupled to the formation or casing with a surface seismic source to measure acoustic travel times from the surface to a range of borehole depths. In this survey, the purpose of the VSP was to calibrate surface seismic profiles to lithology and physical properties characterized from borehole measurements. First arrival measurements (Figure 3) provide an estimate of formation seismic velocities. We can estimate the stacking velocities for direct comparison to surface seismic data by measuring the first motion travel time for each sampled depth. Measurements at a 1.6 ft (0.5 m) interval to a depth of 450 ft were acquired using a sledgehammer seismic source, and measurements at greater depths were acquired using the minivib seismic source used for profile acquisition (see below). Due to well deviation below the cased borehole section and difficulty pulling the geophone across the bottom of casing, a data gap appears between 450–470 ft depths. The sledgehammer source provides frequency signals up to 500 Hz, and the vibroseis source provides signals up to 150 Hz. For signals averaging 2,000 m/s, the hammer VSP samples a wavelength of 13 ft (4 m). An established criterion for seismic resolution is the ¼ wavelength rule (Widess 1973), where seismic boundaries can still be distinguished. Although layers less than a wavelength will not be defined by a separate reflector, interval velocity information can still be obtained.

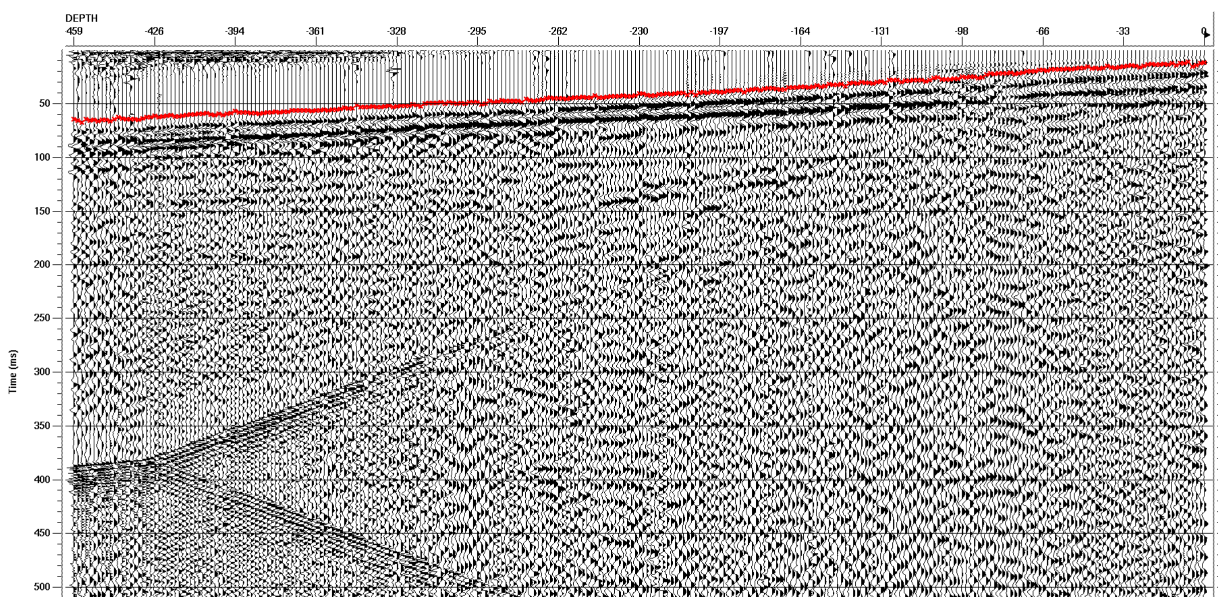


Figure 3. Vertical seismic profile gather with first break arrival picks (red). Note the air wave reflector at 420 ft depth from the water table. Average velocity for first arrival is 2,150 m/s at 450 ft depth. Small variations in travel time with depth provide formation velocity estimates.

The first arrival results show that an average seismic velocity to a depth of 450 ft is 2,150 m/s (Figure 3). Although seismic velocities for carbonate and other lithified material should be greater, the average velocity measurements are strongly influenced by the slow seismic velocities in the upper 10 ft (~200 m/s) and an average velocity in the upper 20 ft of 740 m/s (Figure 3) related to unlithified sediments.

Interval seismic velocities can be calculated using Dix Formula (e.g., Sheriff 2002) to estimate formation velocity and to infer lithologic details within each formation. Figure 4 shows the interval velocity results alongside formation boundaries and natural gamma geophysical logs. Very slow velocities in the upper 20 ft are due to unconsolidated sands that are prevalent throughout the study site. In places, unconsolidated sands are more than 60 ft thick (Figure 2). Below, the Pleistocene Gatuna Formation is predominantly composed of sandstone and conglomerate (Cooper 1960) with low natural gamma values due to the low natural radiation. I calculate seismic velocities of 1,300–2,000 m/s with an average seismic velocity of 1,712 m/s for the Gatuna Formation. The large variation in seismic velocity may be due to partial water saturation, varying degrees of lithification, and grain-size distribution.

At the base of the Gatuna Formation, an abrupt increase in seismic and natural gamma values marks the transition to the Dewey Lake Redbeds Formation that consists of siltstone, sandy shale, shale, and sandstone (Figure 4; Cooper 1960). The higher natural gamma values within the Dewey Lake Redbeds are likely related to increased shale (naturally radioactive material) content, whereas the increase in seismic velocity is likely linked to the grain-size distribution. For example, the increase in seismic velocity and decrease in natural gamma values from 150 to 250 ft depth is consistent with a coarsening downward sequence (increasing sand content with depth) that indicates a transition to a deeper water depositional environment with depth. The high-velocity zone at a 290 ft depth is likely related to a cemented sand (shallow water) unit. The lower portion of the unit (below 300 ft) shows a decrease in seismic velocity and increase in natural gamma values, consistent with an increase in shale content (or coarsening upward sequence) within the formation.

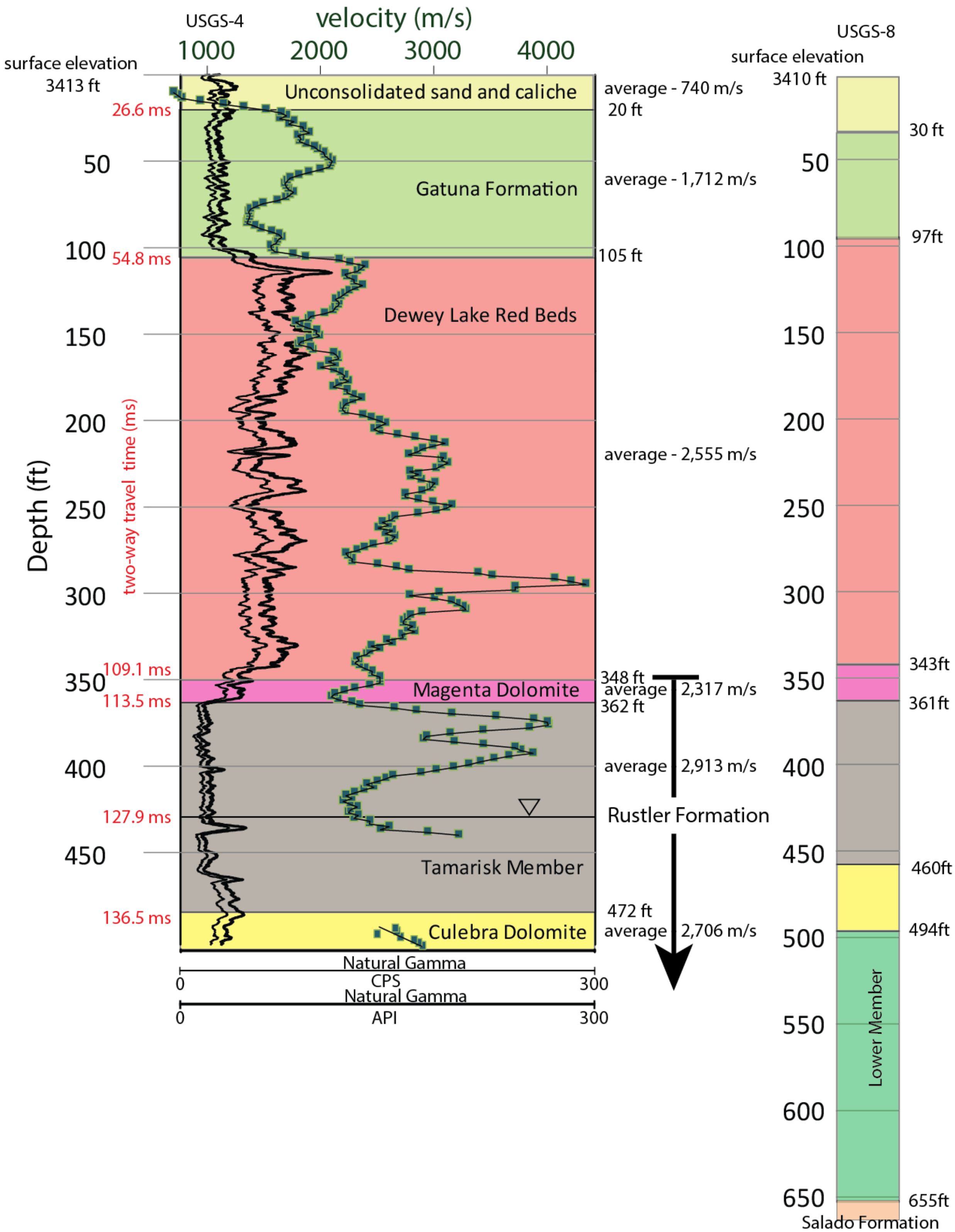


Figure 4. Lithology with depth for wells USGS-4 and USGS-8 (surface location shown on Figure 2). Downhole seismic velocities for USGS-4 were computed from downhole VSP survey, and natural gamma log for USGS-4 was provided by Colog. Note the changing formation depth and thicknesses between USGS-4 and USGS-8 that are located approximately 150 ft apart.

The Rustler Formation consists of various members that include the Forty-Niner (absent in USGS-4), the Magenta, the Tamarisk, and Culebra Members. The Forty-Niner Member consists of siltstone, claystone, and sandstone and appears at the SGZ well (Figure 2). Here, due to the absence of this layer, we do not provide velocity estimates for the Forty-Niner Member (Figure 4). Seismic velocity in uppermost member of the Rustler Formation in USGS-4, the Magenta Dolomite, averages 2,317 m/s, but due to the formation thickness (14 ft) that approaches one wavelength, interval seismic velocity may be overestimated due to a smoothing (running average) function within the Dix formula calculation. The Tamarisk Member consists mostly of anhydrite and gypsum and shows a large variation in seismic velocity. Velocity in the Tamarisk Member averages 2,913 m/s but ranges from 2,000 to 4,000 m/s over the approximately 100 ft sampling depth range. The high-velocity portions of the Tamarisk Member are likely affiliated with anhydrite-dominated layers, and the low-velocity portions of the log are consistent with gypsum-dominated layers. Low natural gamma values in the upper portions of the member are consistent with low natural radiation levels due to the lack of formation shale or clay-rich sands. Due to the well depth, only a few measurements from the Culebra Dolomite Member of the Rustler Formation were obtained with a vibroseis source. These measurements show an average seismic velocity of 2,706 m/s. Both natural gamma and seismic velocity measurements are consistent with the overlying member of the Rustler Formation, and no identifiable geophysical signature is apparent from USGS-4 at this member boundary.

Seismic Reflection Survey

We acquired approximately 13.9 miles (22,365 m) of seismic reflection data along seven profiles using the University of Alberta 17,000-pound IVI Minivib vibroseis truck (Figure 2). We acquired all seismic data with a 16 ft (5 m) source and receiver spacing along existing roads within the Gnome-Coach site (Figure 2). Profile details are summarized in Table 1, where station values represent the distance (in 5 m station increments) from the profile start. We recorded uncorrelated, off-end, 12-second sweeps from 20 to 160 Hz with a 192 channel Geometrics Geode (www.geometrics.com) seismic system. We used 10 Hz geophones at offsets up to 3,150 ft (960 m) to image strata in the upper few thousand feet (upper 1 km). Most geophones were placed along road shoulders, and most vibroseis source stations were located on the roads between each geophone. Processing steps included vibroseis correlation, velocity analysis, deconvolution, band pass filters, mutes, static corrections, and post-stack migration (e.g., Yilmaz 1987). The seismic wavefield from the origin to travel times less than the air wave direct arrival (<330 m/s) were removed due to the strong ground roll and air wave energy overwhelming the seismic reflection energy, and faster surface waves were attenuated with a frequency-offset fan filter. Due to the fast velocity of the reflections below unconsolidated sand, this data mute significantly improved the quality of the stacked sections (Figures 5 through 11). I migrated each profile using a post-stack Kirchoff time migration that places the reflectors from their imaging points to the proper spatial and temporal positions. I converted seismic sections to depth using average velocity values obtained from refracted head wave, stacking velocity values, and borehole seismic (VSP) log (Figure 4). Interval seismic velocities from the upper tens of feet range from 500 to 800 m/s, consistent with unsaturated, coarse-grained alluvial sediments (e.g., eolian sands). Stacking seismic velocities increase from about 1,500 m/s immediately below the surface to more than 6,000 m/s at depths greater than 2,000 ft.

Table 1. Seismic line information, including line number, starting station number, ending station number, total line distance, and station locations for line crossings.

Line No.	Start station	End station	distance (m)	distance (miles)	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7
Line 1	1001	1600	2,995	1.9	-			1242/ 4302	1001/ 5680		
Line 2	2001	2336	1,675	1.0						2092/ 6170	
Line 3	3001	3576	2,875	1.8				3338/ 4508	3505/ 5454		
Line 4	4001	4672	3,355	2.1	1242/ 4302		3338/ 4508				
Line 5	5001	6048	5,235	3.3	1001/ 5680		3505/ 5454			5525/ 6028	
Line 6	6001	6864	4,315	2.7		2092/ 6170			5525/ 6028		6387/ 7318
Line 7	7001	7384	1,915	1.2						6387/ 7318	
Total			**22,365**	**13.9**							

Seismic Results

Line 1

The 1.9 mile (2,995 m) seismic Line 1 was acquired February 28–March 1, 2012, along a secondary dirt road and trends west-east through the Gnome-Coach site, south of SGZ (Figure 2). The profile begins immediately east of Line 5 and crosses Line 4 at station 1242 with a decrease in elevation of approximately 70 ft along the eastern portion of the profile (Figure 5). Due to dry sand and lack of solid road surface, sources were not acquired between stations 1270 and 1370. Because receiver stations were acquired within the sand dune section, depths more than 500 ft still contain usable reflection information. The projected location of the SGZ well is at station 1125, and the projected location to well USGS-1 is station 1050.

Seismic reflection data quality is better along the western portions of Line 1 (Figure 5), possibly due to improved source/receiver coupling or a consistent thickness of near-surface unconsolidated strata. Reflections along Line 1 extend from the surface to depths that exceed 2,000 ft (Figure 5). Reflector depth increases to the east near the center of the profile along the deeper reflectors. This increase in depth to the east is consistent with regional interpretations for the top of the Castile Formation at 2,000–2,300 ft depth (Gard 1968). However, this abrupt step in formation depth is more consistent with a fault and not a gentle formation dip to the east (Figure 1). The short-wavelength topography on the deeper reflections, specifically along the eastern portions of the profile, may be related to near-surface static effects from varying unconsolidated (eolian) deposit thicknesses.

The shallowest reflector on the seismic profile correlates to the top of Gatuna Formation (Figure 5). This reflector is located less than 100 ft below land surface, ties to contact depths observed in SGZ and USGS-1 wells, and is best observed between stations 1100 and 1250. Additional reflectors in the upper 500 ft are also evident, but due to the distance to the nearest well, it is difficult to tie individual reflectors to lithologic contacts. Below 500 ft depth, a lack of reflectivity is consistent with a uniform salt layer within the Salado Formation. East of station 1400, reflectors show significant topography. The top of Castile Formation still appears below this portion of the profile, suggesting that energy penetrates the shallow section, but the lack of higher-frequency signal at depth may result from short-wavelength scattering effects. Nearby seismic profile interpretations (described below) aid the Line 1 interpretation, but the lack of reflector continuity along the eastern portion of the profile leads to greater uncertainties in interpretation.

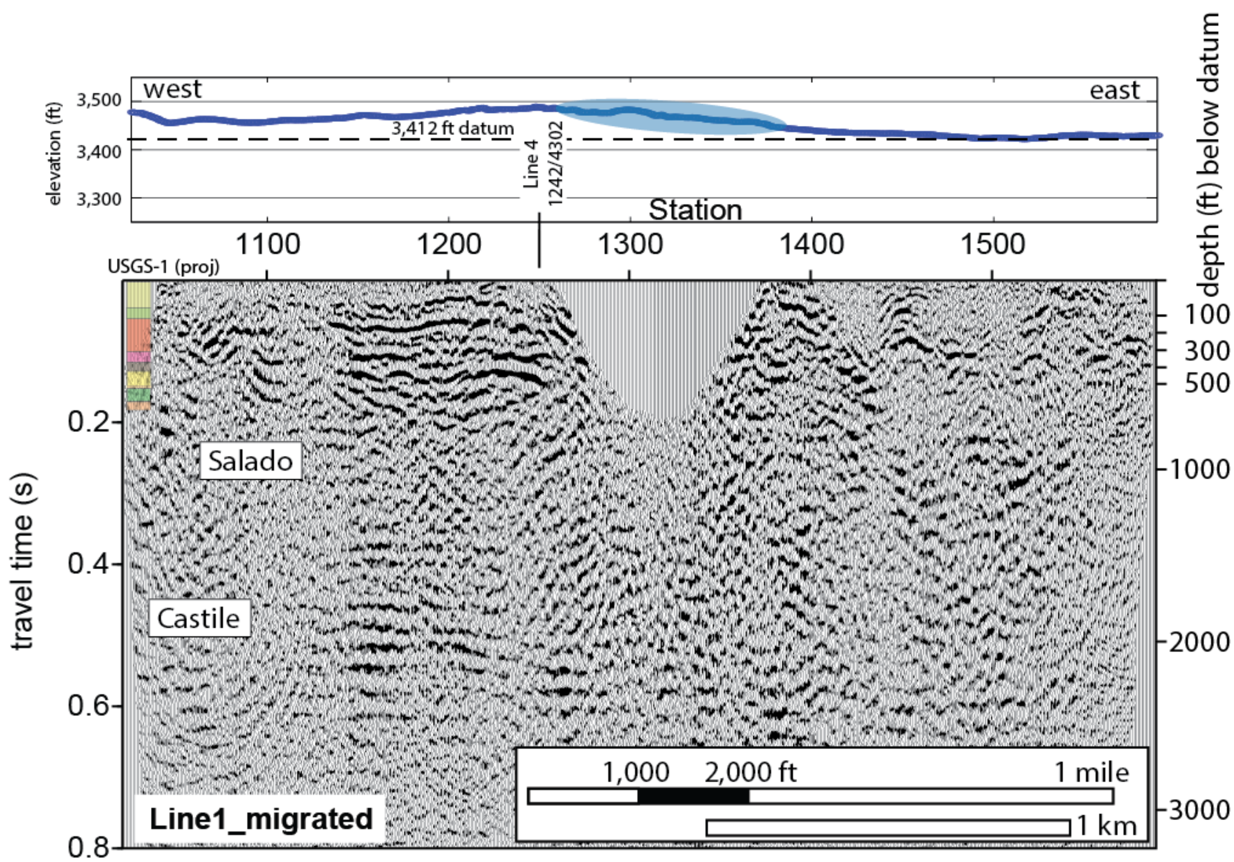


Figure 5. Seismic image and elevation profile for Line 1. The projected position for the SGZ well is near station 1125, while USGS-1 projects to the west end of the profile. Sources were not acquired between stations 1275 and 1375 due to deep sand. Seismic profile location is shown on Figure 2.

Line 2

The 1.0 mile (1,680 m) seismic Line 2 was acquired on March 9 and 10, 2012. The profile was acquired along a dirt access road to wells USGS-4 and USGS-8 (1963 tracer test wells) (Figure 2). The profile trends south-north and decreases in elevation by approximately 60 ft toward the northern portion of the profile (Figure 6). The profile crosses Line 6 at station 2092. Due to a designated exclusion zone, sources were not acquired between stations 2200 and 2250. Because receivers within the exclusion zone recorded sources from outside the exclusion zone, reflections were imaged at depths greater than 500 ft along the length of the profile. USGS-4 monitoring well is located approximately 350 ft east of station 2190, and USGS-1 is located approximately 2,500 ft east of station 2100. Lithologic logs from both wells are shown on Figure 6.

Reflections along Line 2 extend from the surface to depths that exceed 2,000 ft (Figure 6). A prominent reflector at about the 2,200 ft depth likely represents the top of the high-velocity, anhydrite-dominated Castile Formation (e.g., Cooper 1960; Figure 1), while shallower reflectors contain significant topography and tie to lithologic contacts observed in nearby boreholes. At the projected position of well USGS-4, reflectors tie to the top and bottom of the Gatuna Formation and top of Rustler Formation (Figures 3 and 4). The reflector associated with the top of Gatuna sandstones approaches the surface at station 2050 and increases in depth farther north and south. This pattern is consistent with alluvial sand that appears adjacent to the road surface along much of the profile, with the surface sands missing adjacent to the Line 6 profile. Although a reflector that correlates to the Gatuna/Dewey Lake Formation unconformable contact is observed adjacent to the USGS-4 projected position, changing amplitudes likely result from the large variation in seismic velocity within the Dewey Lake Redbed Formation and erosional nature of the formation top. A large-amplitude reflector that extends along the length of the profile also correlates with the Dewey Lake/Rustler Formation contact at a depth range of 300–400 ft. The tracer test was in the Culebra Member of the Rustler Formation at a depth of about 470 ft. Lastly, the top of Salado Formation appears at a depth of 713 ft in the nearby USGS-1 borehole and a depth of 650 ft in USGS-8 (Figure 2). A reflector that ranges in depth from 600 to 800 ft likely represents the top of Salado Formation. This formation upper contact shallows to the north and south with a synform centered at station 2130 and an antiform centered at station 2220. It is unclear whether the changing reflector depth is due to the depositional environment, structural controls, or dissolution within the carbonate and salt members of the Rustler and Salado Formations.

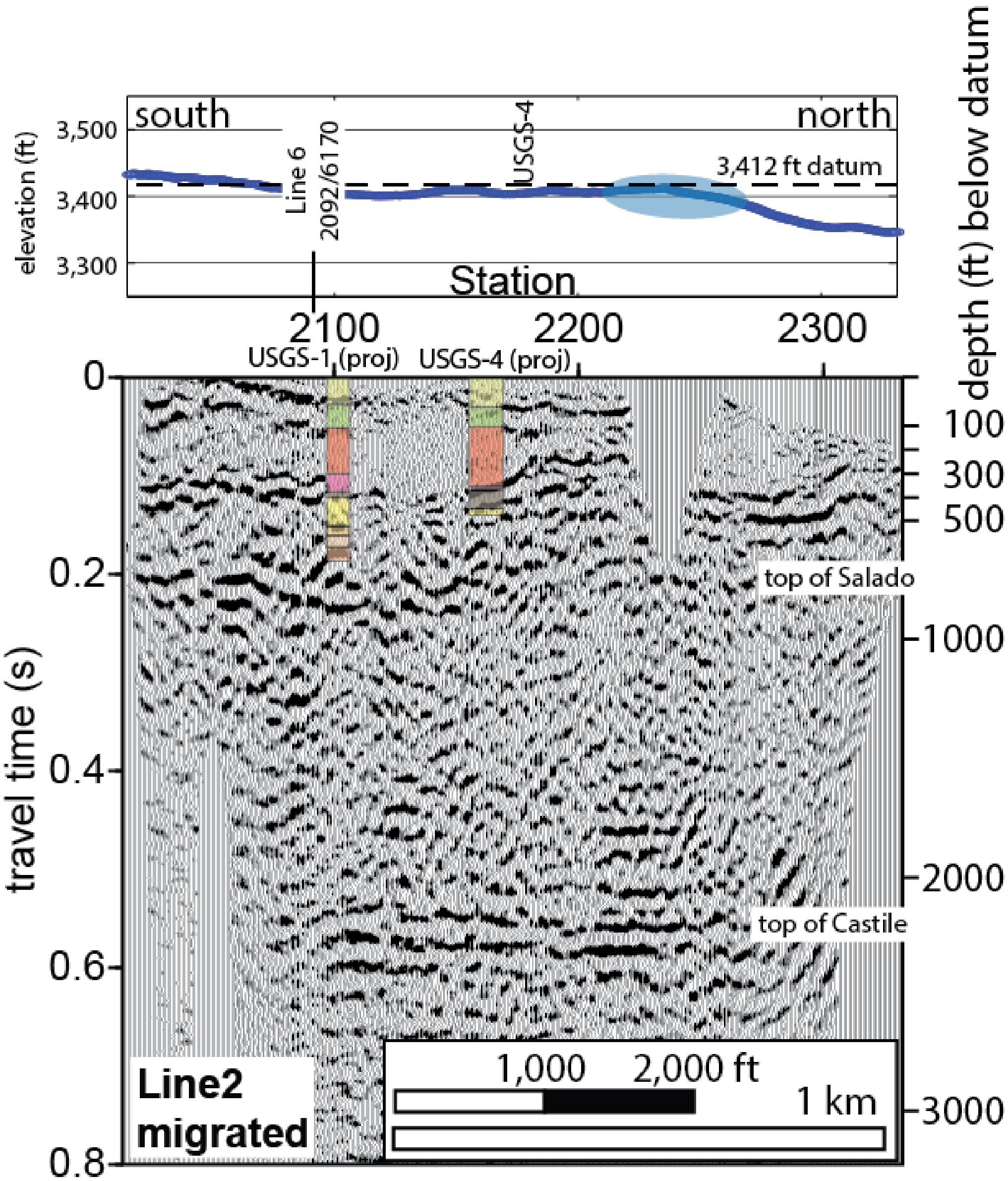


Figure 6. Migrated seismic image and elevation profile for Line 2. The projected position for well USGS-4 is near station 2175, and well USGS-1 is near station 2100. Sources were not acquired between stations 2220 and 2250 due to a designated exclusion zone. Seismic profile location is shown on Figure 2.

Line 3

The 1.8 mile (2,880 m) seismic Line 3 was acquired on March 2 and 3, 2012, along a dirt road that trends east-west through the Gnome-Coach site (Figure 2). The profile crosses Line 4 at station 3338 and Line 5 at station 3505. The topography along Line 3 varies less than 50 ft (Figure 7). Due to an archaeological exclusion zone, sources were not acquired between stations 3231 and 3238. However, because geophones recorded source shots on both sides of the exclusion zone, reflections were recorded beneath the exclusion area. Line 3 crosses the SGZ well at station 3457.

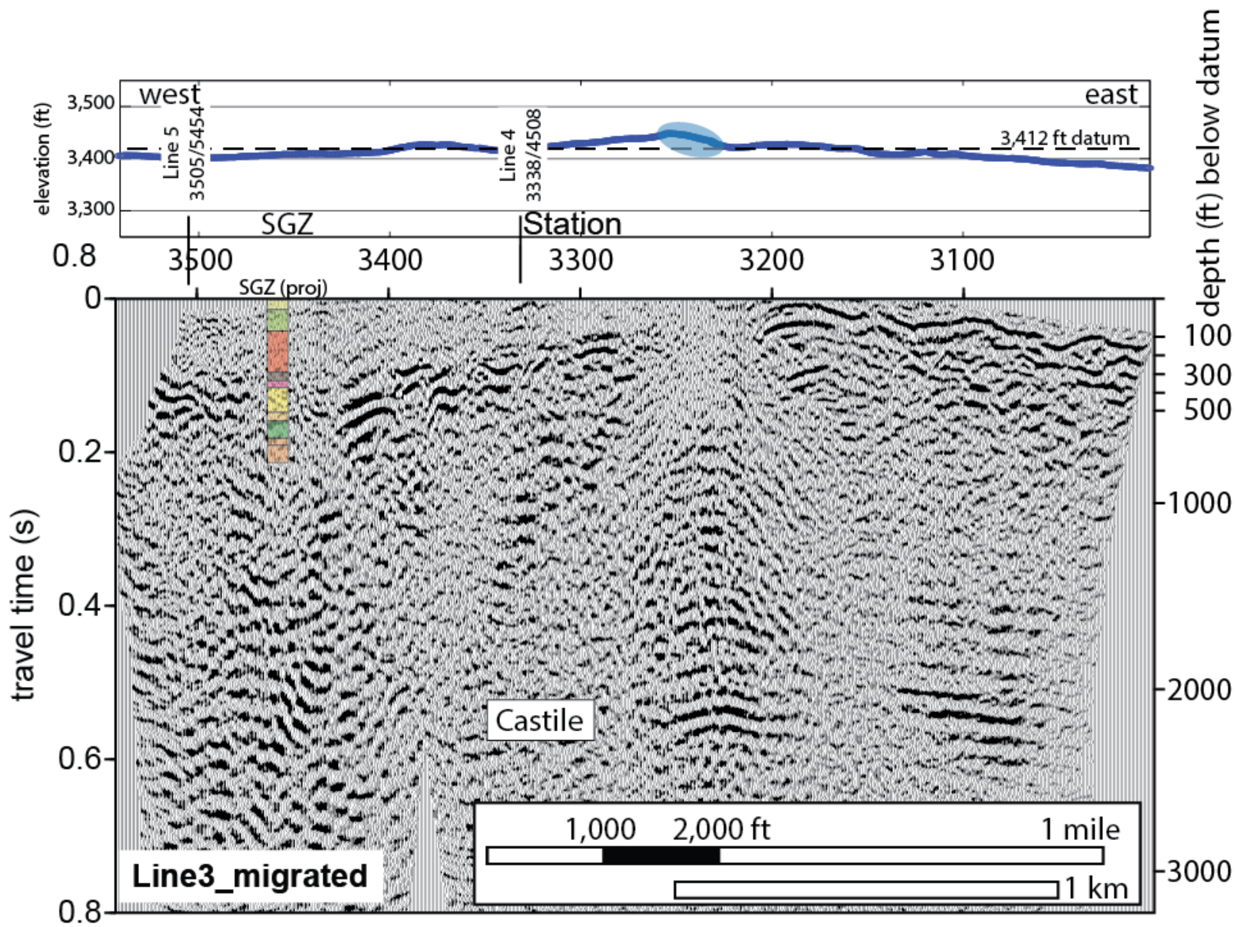


Figure 7: Seismic image and elevation profile for Line 3. The projected position for the SGZ well is near station 3450. Sources were not acquired between stations 3235 and 3245 due to an archaeological exclusion zone. Seismic profile location is shown on Figure 2.

The seismic character along Line 3 is highly variable (Figure 7). Reflections along Line 3 extend from the surface to depths that exceed 2,000 ft. A prominent reflector from the 2,000 to 2,200 ft depth likely represents the top of high-velocity anhydrite-dominated Castile Formation (e.g., Cooper 1960; Figure 1). Although the top of Castile Formation is poorly imaged west of station 3300, reflections at this depth increase in depth both east and west of station 3220. Whereas reflections shallower than about 300 ft are absent near SGZ, the area east of the Line 4 crossing shows reflectivity in the upper few hundred feet (Figure 7). Since no well logs are available within the northeast quadrant of the Gnome-Coach site, the stratigraphic interpretation from the eastern portion of the profile is based on seismic character.

Where Line 3 crosses the SGZ well, a prominent reflector appears from the 200 to 400 ft depth that ties to the top of Rustler Formation (Figures 2 and 7). This reflector dips toward the SGZ site in what appears as a structural or stratigraphic low. At approximately 300 ft from the SGZ borehole, reflectivity is absent, possibly related to blast effects and the formation collapse within the Salado Formation. Farther east, the top of the Rustler shallows to within about 150 ft of ground surface. Below the exclusion zone (centered at station 3250), reflectivity in the upper few hundred feet is absent, likely due to the lack of near-offset source-receiver pairs within the exclusion zone. East of station 3200, a strong undulating reflector at depths shallower than 100 ft likely is associated with the top of the Rustler Formation (to correlate with the uppermost reflector west of the exclusion zone). Although regional well logs show formation contacts increasing in depth east of the Gnome-Coach site, the west-dipping top of the Rustler Formation reflector from stations 3450 to 3200 suggests that the Gatuna Formation may be absent within the northeast quadrant of the site. However, the Gatuna Formation was encountered in borehole ERDA-10 at 150 feet below ground surface to the north of line 3. Reflectors at all depths change dip direction east of station 3150, perhaps suggesting that a broad structural fold controls stratigraphic depths beneath Line 3.

Line 4

The 2.1 mile (3,360 m) seismic Line 4 was acquired on March 5 and 6, 2012, along a dirt road and trends south-north through the Gnome-Coach site (Figure 2). The profile crosses Line 1 at station 4302 and Line 3 at station 4508. The profile was acquired on a hard-packed access road between stations 4050 and 4300 and along a loose, sandy access road between stations 4300 and 4600. The profile crests a hill at station 4270 and decreases in elevation by more than 100 ft to the north (Figure 8). Station 4500 is located approximately 2000 ft east of SGZ.

Strong reflectivity appears along the southern portions of the profile while poor source-receiver coupling along the sandy road may have resulted in poor data quality between stations 4350 and 4500. A strong amplitude reflector at the 1900–2000 ft depth likely relates to the top of Castile Formation, shallower than interpretations from previous profiles. This reflector increases in depth to the north with an inflection point near station 4300 and near the crossing of Line 3. This inflection point may be fault related and is similar in reflection character to Line 3 and Line 5 (as discussed below). The change in reflection character to the north of the presumed fault may be coincidental, and it is unclear whether this fault predates the Rustler Formation deposition or whether the fault may influence lateral groundwater flow.

A strong amplitude reflector at approximately 300 ft depth ties to the top of Rustler Formation contact interpreted on Line 3 (Figure 8). Here, an increase in reflector depth below stations 4150 and 4250 may have resulted from dissolution features from the underlying carbonate and/or salt formations. Reflections along the northern portion of Line 4 tie to the top of Dewey Lake, Rustler, and Salado Formations; however, the lack of reflectivity within the region between stations 4350 and 4500 does not provide insight into formation contact depths or geologic structures.

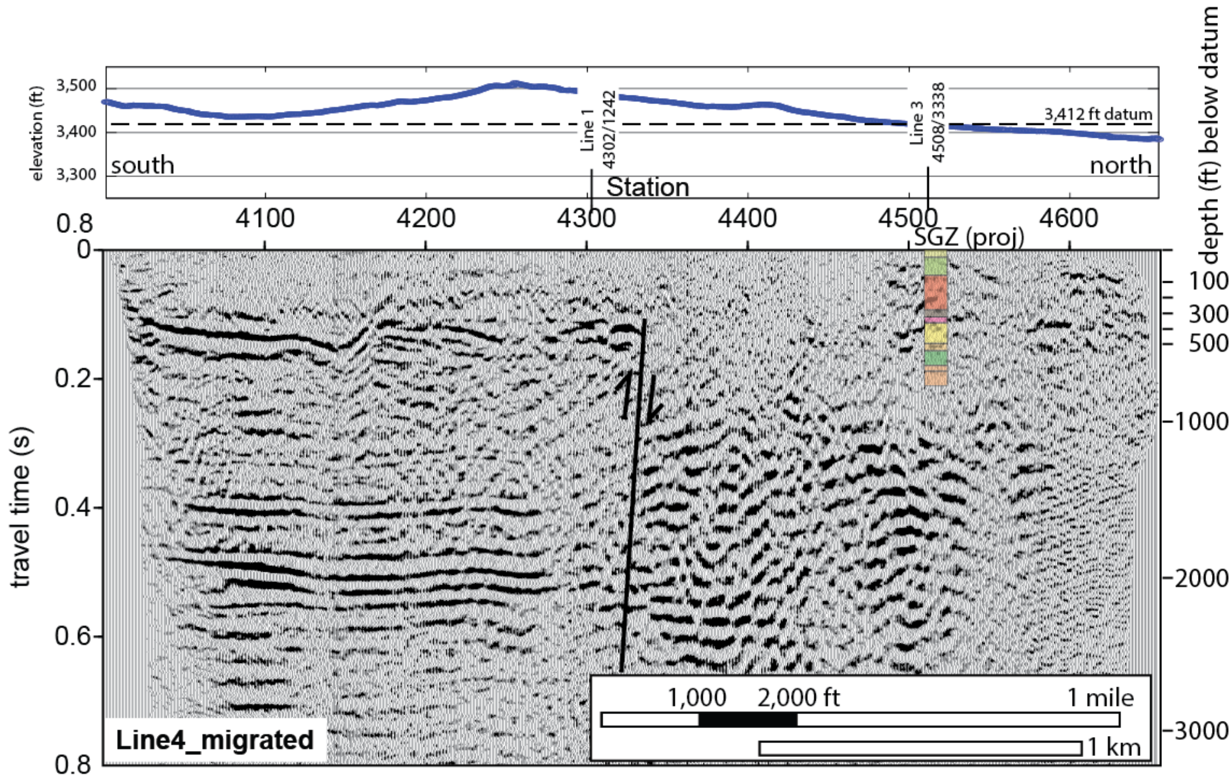


Figure 8: Seismic image and elevation profile for Line 4. The projected position for the SGZ well is near station 4500. Sources were acquired along an established road south of station 4300 and acquired on a sandy track to the north. Seismic profile location is shown on Figure 2.

Line 5

The 3.3 mile (5,240 m) seismic Line 5 was acquired February 23–26, 2012, along the main access (hard-packed) road and trends north-south through the Gnome-Coach site (Figure 2). The profile crosses Line 3 at station 5454, Line 6 at station 5525, and Line 1 at station 5680. A decrease of approximately 250 ft in surface elevation from station 5700 to the north is noted along the profile. A large, sandy hill was encountered along this profile between stations 5600 and 5700. Within this region, many source stations were not occupied, and geophones were deployed in dry, loose sand. Seismic data quality is highly variable along the profile (Figure 9).

Reflections along the profile extend to more than 2,000 ft depth (Figure 9). Between 2,000 and 2,200 ft depth, a strong amplitude reflector corresponds to large seismic velocity change and to the top of the Castile Formation. Stacking velocities for this depth exceed 6,000 m/s, consistent with seismic velocity of anhydrite. The top of Castile Formation appears flat along the southern and northern portions of the profile with an approximately 200 ft change in reflector depth between stations 5500 and 5700. Near station 5350 on the northern portion of the profile the Castile Formation was encountered in borehole ERDA-10 at 2337 ft below ground surface. Topographic changes along the Castile Formation contact on the southern portion of the profile may be due to a fault, consistent with offset observed on the parallel Line 4 and perpendicular Line 3. If these reflector steps are related, a west-northwest-trending, high-angle thrust fault is consistent with the interpreted offset and orientation. The lack of reflectivity north of the interpreted fault along Line 5 may explain the poor reflectivity at depth along the western portions of Line 3 that may be aligned with the footwall of the fault. Reflector offsets shallower in the section are not obvious, and this fault may not offset Rustler or shallower strata.

Along the southern portion of Line 5 (stations 5700–6000), a prominent reflector that appears at about 300 ft depth ties to the top of Rustler Formation. A deeper reflector that ranges in depth from 600 to 1,000 ft may correlate with the top of Salado Formation; however, this depth is greater than the Salado Formation contact in nearby well USGS-2. This reflector contains significant topography that may be the result of broad dissolution features within the Salado Formation. The lack of topography on reflectors both above and below this contact suggests that the unit thickness is near constant and that the reflector depth may reflect lateral changes in deposition.

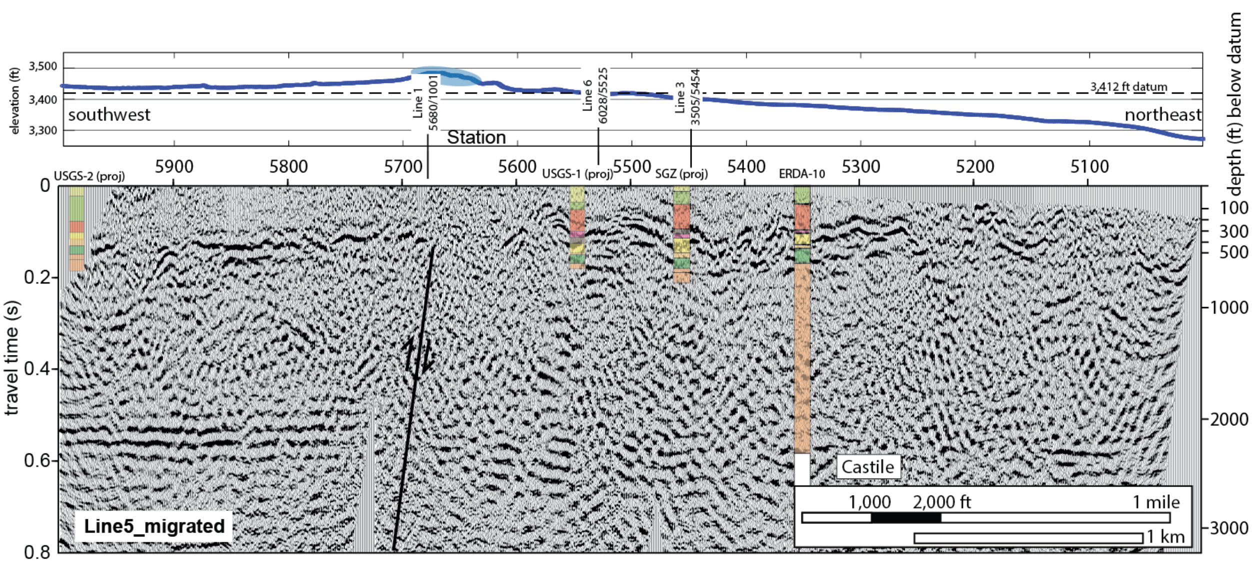


Figure 9. Seismic image and elevation profile for Line 5. Well logs from SGZ, USGS-2, and USGS-4 wells appear at the nearest projected position. Sources were not acquired between stations 5620 and 5700 due to deep sand and a steep hill. Seismic profile and well locations are shown on Figure 2.

Within the central and northern portions of Line 5, significant reflector topography in the upper few hundred feet suggests a complex geologic setting. Given that the profile was acquired along the main Gnome-Coach access road; I do not attribute this reflector topography as related to near-surface static effects. Reflectors tie to the top and base of Dewey Lake Formation, and top of Salado Formation. Reflectors shallow between stations 5450 and 5600 and crest near station 5500 in an antiform structure. Here, the Gatuna Formation may be absent due to erosion. Near station 5400, the top of Rustler Formation is at its deepest point along this portion of the profile (local synform). Along the northern portion of the profile, reflectors are difficult to track in the upper few hundred feet below land surface. Because reflectivity from the top of Castile Formation is present, the lack of near-surface reflectivity along a hard-packed road surface may suggest changing lithology from other portions of Line 5.

Line 6

The 2.7 mile (4,315 m) seismic Line 6 was acquired March 6–8, 2012, along the main access road through the Gnome-Coach site. This profile represents the southwest continuation of the Line 5 profile along the main Gnome-Coach access road (Figure 2). The profile duplicates the Line 5 stations between 6001 and 6028 (Line 5 stations 5498 and 5525), crosses Line 2 at station 6170, and crosses Line 7 at station 6387. Dry sand conditions appear along the surface at station 6600 to 6650, but the remainder of the profile was acquired on a solid road surface. Surface elevation along the profile decreases by approximately 200 ft west of station 6300 (Figure 9).

Reflections along the profile extend to more than 2,000 ft depth (Figure 9). Between 2,000 and 2,300 ft depth, a strong amplitude reflector corresponds to large seismic velocity change and to the top of the Castile Formation. Stacking velocities for this depth exceed 6,000 m/s, consistent with seismic velocity of anhydrite. A gentle westward dip of the Castile Formation west of station 6,200 contradicts the regional trend (Cooper 1960), but the eastern portion of the profile shows a gentle eastward dip to the reflector. Topographic changes along the Castile Formation contact may be due to faulting or dissolution effects, and a discrete reflector step near station 6500 is consistent with a high-angle thrust fault. Reflector offsets shallower in the section are not obvious, and this fault may not offset Rustler or shallower strata.

Reflections in the upper 1,000 ft suggest a complex stratigraphy within the Salado, Rustler, and Dewey Lake Formations. The uppermost reflector that ranges from 100 to 300 ft below land surface likely correlates with the top of Rustler Formation. Given that the Gatuna Formation does not exceed 50 ft in thickness in this area and that the topography decreases by more than 200 ft along the western portions of the profile, this formation is likely thin to non-existent to the west of station 6300. The significant change in reflector depth may best represent an unconformity at the top of Rustler Formation in the absence (in USGS-2 and USGS-4 wells) of the uppermost Forty-Niner Member or solution and collapse of underlying carbonate members of the Rustler Formation (Gard 1968).

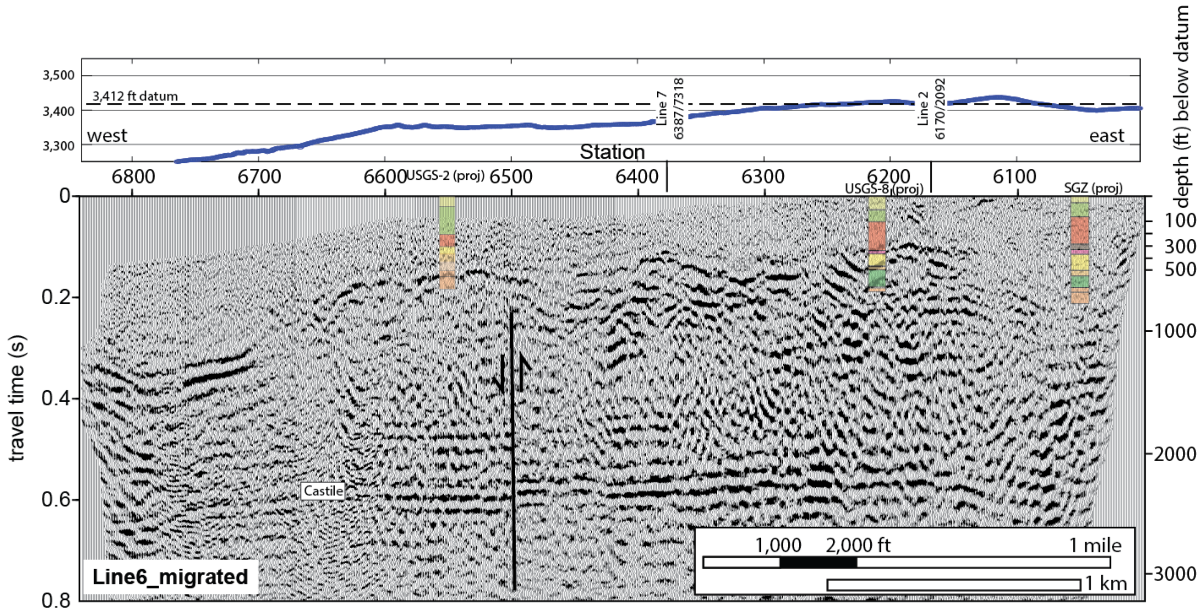


Figure 10: Seismic image and elevation profile for Line 6. Lithologic contacts from the (projected) wells USGS-2, USGS-8, and the SGZ well are superimposed on the seismic profile. Seismic line and well locations are shown on Figure 2.

Line 7

The 1.2 mile (1,915 m) seismic Line 7 was acquired on March 9, 2012. The profile was acquired along a south-north access road to a water tank facility southwest of SGZ (Figure 2). The profile crosses Line 6 at station 7318 and decreases in elevation by approximately 50 ft from south to north (Figure 10). The USGS-2 well is located less than 0.5 mile from the south end of the profile, and USGS-4 is located approximately 1.0 mile northeast of the north end of the profile.

A prominent reflector at 2,100–2,200 ft depth likely represents the top of high-velocity (>6,000 m/s) anhydrite-dominated Castile Formation (e.g., Cooper 1960; Figure 11). Topographic changes along the Castile Formation may due to faulting or dissolution effects (changes in lateral velocity) from the overlying limestone/salt strata. Given the increase in reflector depth to the south along this profile and west along Line 6, I interpret a northwest-striking thrust fault that bisects Lines 6 and 7. This fault orientation is consistent with regional structures (e.g., Cooper 1960), but the effects on near-surface stratigraphy and groundwater flow are unclear.

Due to the lack of unconsolidated sand that appeared along the surface of this profile, no clear reflector is observed for the top of Gatuna Formation (Figure 11). The prominent reflector that ranges in depth from 300 to 400 ft along the length of the profile may be too deep to represent the base of Gatuna Formation unconformity. The undulating nature and depth of the reflector may best represent an unconformity at the top of Rustler Formation in the absence (in USGS-2 and USGS-4 wells) of uppermost Forty-Niner Member or solution and collapse of underlying carbonate members of the Rustler Formation (Gard 1968). Along the southern portion of the profile, a reflector matches the depth to the top of Salado Formation in USGS-2. The reflector amplitude decreases to the north, likely the result of changing seismic velocities along the formation contact.

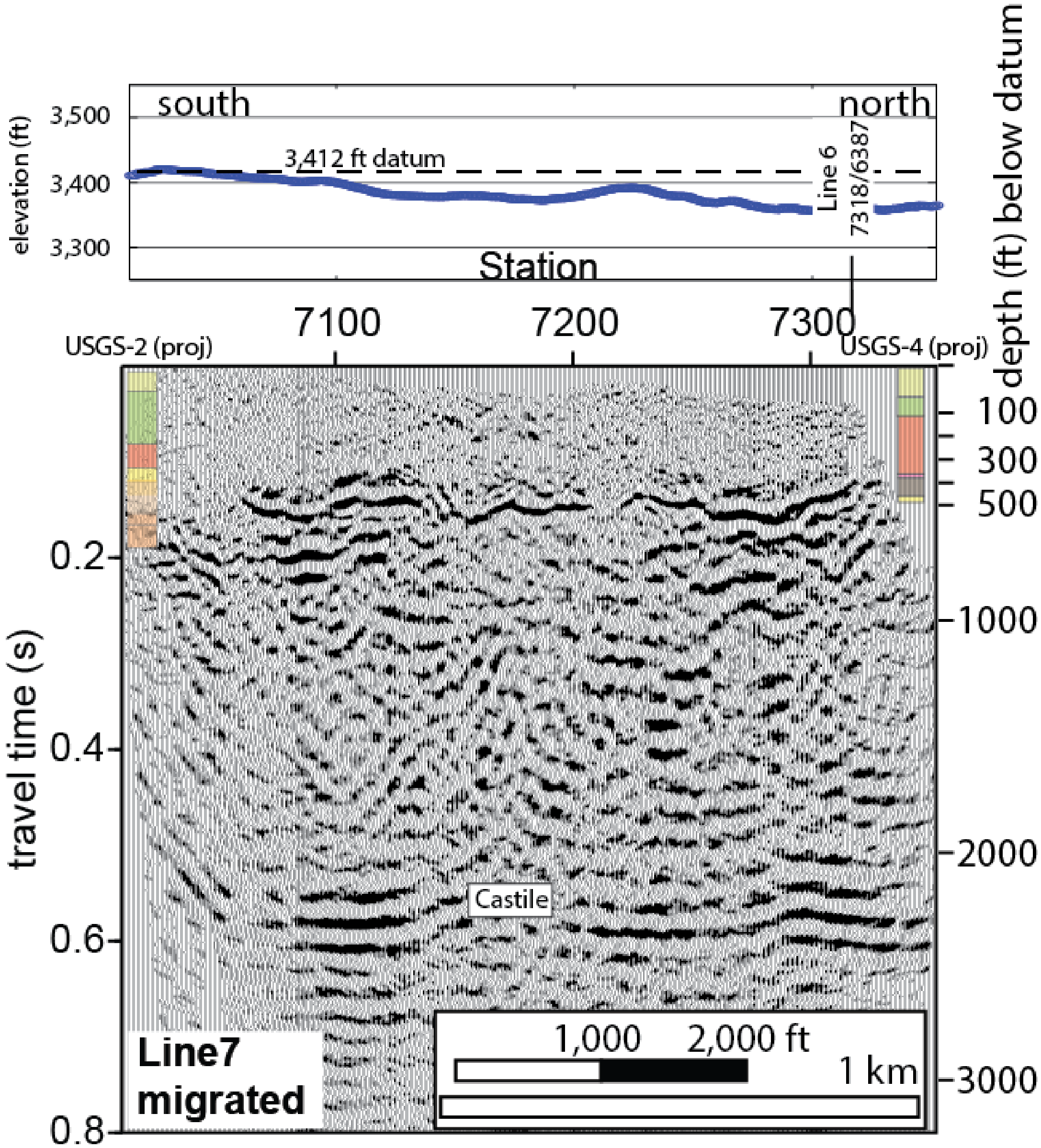


Figure 11: Seismic image and elevation profile for Line 7. Lithologic logs for the USGS-2 and USGS-4 wells are placed along the profile. Sources were not acquired north of station 7320 due to road termination. Seismic profile and well locations are shown on Figure 2.

Conclusions

Seismic reflection results from the Gnome-Coach site show stratigraphy in the upper few thousand feet of depth. I interpret the top of the Castile Formation to range from 1,900 to 2,400 ft below land surface. A shallowing of the top of Castile Formation by more than 300 ft is observed on Line 5 between stations 5600 and 5800, on Line 6 between stations 6150 and 6400, and Line 4 between stations 4000 and 4500. Assuming this horst block is fault controlled, I interpret northwest-striking faults that bisect the Gnome-Coach site west of the SGZ well. Given the variation in near-surface stratigraphy, it is difficult to assess the effects of this fault on groundwater flow. An additional step in the Castile Formation is located along Line 6. Here, the Castile Formation steps down to the west by less than 50 ft. The increase in Castile Formation depth to the west contrasts with the regional interpretation (Cooper 1960) and likely represents local topography and faulting.

Reflectivity in the Salado, Rustler, Dewey Lake, and Gatuna Formations is highly variable both laterally (Figures 4–11) and vertically (Figure 3). Erosion, dissolution, and complex depositional environments probably strongly influence groundwater flow in this part of the section.

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