RECLAMATION
Managing Water in the West

Technical Memorandum 85-833000-2017-14

Compilation of Well Data in the Vicinity of Paradox Valley, CO

Colorado Basin Salinity Control Project, Paradox Valley Unit, Colorado Upper Colorado Region

U.S. Department of the Interior
Bureau of Reclamation

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Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Seismology, Geomorphology, and Geophysics Group, 86-68330

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Peer Review Certification

This report has been reviewed and is believed to be in accordance with the service agreement and standards of the profession.

Peer reviewed by:

Lisa V. Block, geophysicist — 7/11/2017 Date

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1 Introduction

The Bureau of Reclamation (Reclamation) operates a deep injection well at Paradox Valley in western Colorado (Figure 1-1), as part of the Paradox Valley Unit (PVU) of the Colorado River Basin Salinity Control Program (CRBSCP). Paradox Valley, overlying a salt anticline, is a major contributor to the salt load of the Colorado River. The Dolores River, a tributary of the Colorado, picks up about 205,000 short tons (185,000 metric tons) of salt annually from natural brine inflows as it crosses Paradox Valley. PVU was authorized for construction by the Colorado River Basin Salinity Control Act of 1974 (Public Law 93-320; amended in 1984 as Public Law 98-569).

The purpose of PVU is to divert up to 90 percent of the Paradox Valley brine inflows from entering the Dolores River, where they would substantially degrade water quality. Subsurface brine flows are intercepted by long-term pumping from a field of shallow extraction wells located along the river. The extracted brine is then collected and filtered at a surface-treatment facility, piped about 3.6 miles (6 km) to an injection facility at the edge of the valley, and finally injected into a 15,900-ft (4.8-km) deep injection well for long-term disposal. The injection well, identified as PVU Injection Well #1, is designed to dispose of brine deep underground, confined to a narrow target zone extending over only the lowest 1,700 ft (500 m) of the borehole. Within this target zone, most of the injected brine is taken up by the Leadville formation, a subhorizontal formation of Mississippian-age limestone. The overlying Paradox formation, which contains thick layers of impermeable salt, acts as a confining layer.

In recent years, the pressure required to inject the brine has been increasing and, prior to a decrease in the injection flow rate in mid-2013, was approaching the maximum allowable surface injection pressure as permitted by the U.S. Environmental Protection Agency (EPA). Various options are under consideration to reduce surface pressures without further reductions in flow rate, including drilling a second injection well.

In order to determine the best site for a second injection well, it is necessary to refine our model of the subsurface geologic structure in the vicinity of Paradox Valley. We are in the process of creating an integrated geologic model incorporating data from existing seismic reflection surveys and well logs, a new aeromagnetic survey, Interferometric Synthetic Aperture Radar (InSAR), and hypocenters of induced earthquakes.

As part of these efforts, the Bureau of Reclamation has licensed approximately 570 miles of seismic reflection data. Approximately 70 miles of data were used in a “Phase I” interpretation of the area around the injection well, while all 570 miles of data were used in a “Phase II” interpretation of the entire Area of Interest (AOI), shown in Figure 1-1. The AOI is a polygon that bounds the area in which sites for drilling a second injection well are being considered.

The purpose of this TM is to describe the well data that have been compiled as part of the larger second well site investigations. These data were integral to the interpretation of the seismic reflection surveys mentioned above. An overview of the other subsurface studies that comprise the second well investigations, and references to detailed reports on each study, can be found in King et al., 2017.

Several types of well data were compiled for the purposes of this report. A GIS database of oil and gas wells in the vicinity of Paradox Valley was compiled in June 2015. All known oil and gas wells that are at least 6000 feet deep and within 25 kilometers (km) of the AOI are included. The information was compiled from three sources: the websites of the Colorado Oil and Gas Conservation Commission (COGCC), the Utah Division of Oil, Gas, and Mining (UTDOGM), and IHS Energy Lognet. The GIS database includes basic information about each well, including its name, operator, location, depth, date (either spud date or completion date), and API identifier. In addition, it includes information about the depths at which key formations were penetrated, the formation at total depth, and whether sonic logs are available and have been acquired by Reclamation.

Additionally, digital well log data were obtained from 90 wells. While sonic logs were of primary interest, other types of logs were also acquired, including gamma ray and density logs. The majority of the well logs from the PVU Injection Well #1 existed only in one or two hardcopies, so these logs were also scanned and digitized.

The well log data have two main purposes. The first purpose is to provide information that can be used in the interpretation of the seismic reflection data. Well logs are used to create synthetic seismograms, which are needed to tie seismic reflectors to the formations they represent. In addition, formation depths determined from well logs are used to convert seismic reflection travel times to depths. The Leadville formation and Paradox formation are the primary formations of interest, as these formations serve as the primary injection target formation and confining formation, respectively, in the existing injection well, and are likely to serve the same roles in a second injection well. The second purpose of the well log data is to provide information about formation characteristics, particularly the porosity, which influence the storage volume and the pressure response of potential reservoir formations.

Section 2 of this TM describes the data sources from which the well data were compiled. Section 3 describes the GIS database, and includes interpolated surfaces created from the formation tops. Section 4 details the well logs that have been compiled, both for PVU Injection Well #1 and for other wells in the area, including the types of well log analyses that have been conducted.

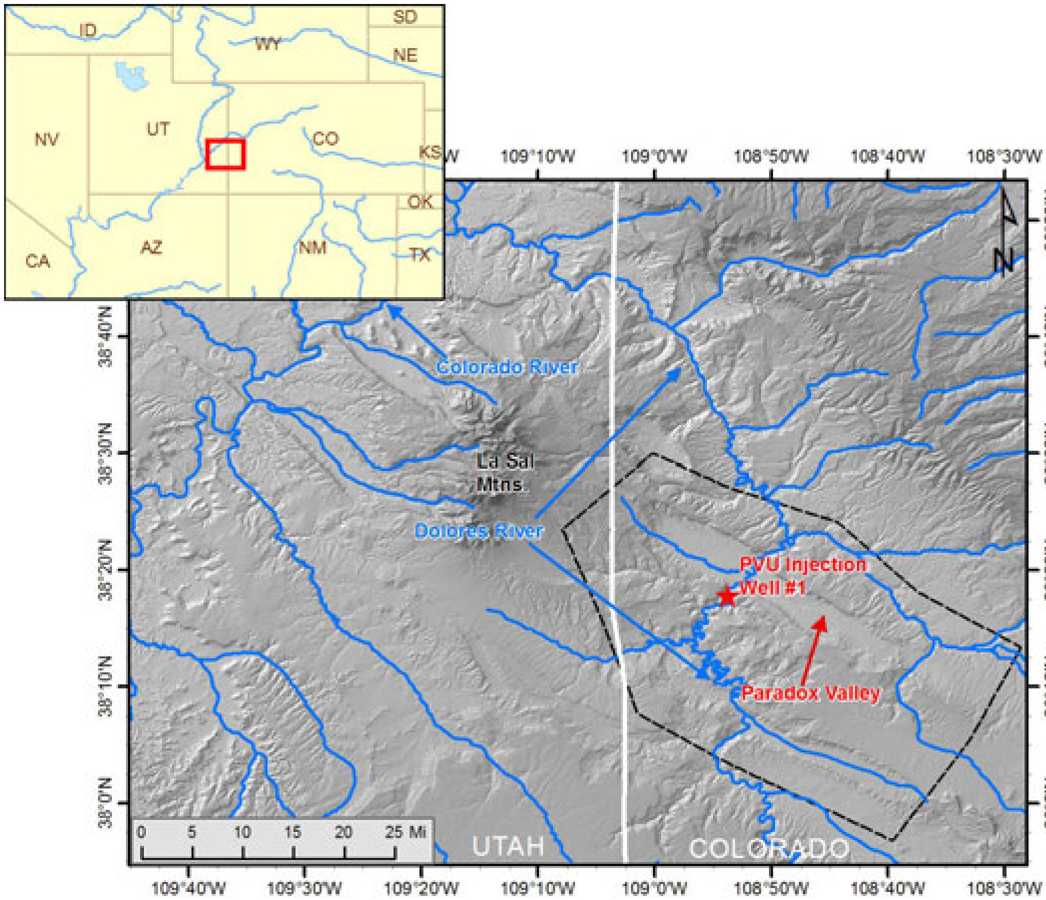

Figure 1-1. Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado. Dashed line outlines the area of interest (AOI).

2 Data Sources

The information described in Sections 3 and 4 of this TM was compiled from six sources: the COGCC, UTDOGM, IHS Energy Lognet, internal government reports written in the 1980s, a database of Paradox Basin formation tops created and maintained by consultant Don Rasmussen, and formation tops determined by the seismic interpretation contractor on this project, International Reservoir Technologies, using well log correlation. More details about each source are given below.

2.1 COGCC

The Colorado Oil and Gas Conservation Commission (COGCC) is a division of Colorado's Department of Natural Resources. It maintains a database of information about Colorado's oil and gas wells called the Colorado Oil and Gas Information System (COGIS), at the website http://cogcc.state.co.us/data.html#/cogis. Additionally, an ArcGIS shapefile of well surface location data is updated daily and available for download at the website http://cogcc.state.co.us/data2.html#/downloads. This shapefile, last downloaded on June 29, 2015, was used to identify the wells within 25 km of the AOI. Additional information about the wells was then added by querying the database using each well's unique identification number, known as its API number.

For the majority of wells, a number of scanned documents are included with the database entry for that well. While there is significant variability in what documents are available for each well, they often include drilling reports, completion and abandonment reports, surveys, and raster images of well logs. We obtained digital well logs in Log ASCII Standard (LAS) format for three wells from the COGCC. We also obtained raster images of well logs for an additional 43 wells and had them digitized into LAS format by LogDigi.

2.2 UTDOGM

The Utah Division of Oil, Gas, and Mining is a division of Utah's Department of Natural Resources. It maintains a database of information about Utah's oil and gas wells at the website http://oilgas.ogm.utah.gov/Data_Center/DataCenter.cfm. Additionally, an ArcGIS shapefile of well surface location data is updated daily and is available for download at the website http://gis.utah.gov/data/energy/oil-gas. This shapefile, last downloaded on March 19, 2015, was used to identify the wells within 25 km of the AOI, and additional information about the wells was added by querying the database using well APIs.

Like the COGCC's database, scanned documents are included with the database entries for a majority of wells. It is also possible to query this database for well logs or formation tops. We obtained a raster image of a sonic log for 1 well from the UTDOGM and had it digitized into LAS format by LogDigi.

2.3 IHS Energy Lognet

IHS Energy is a division of the company IHS, a global information company. IHS Energy maintains a database of well logs for purchase, at the website https://ihslognet.ihsenergy.com. Both digital logs, in LAS format, and raster logs are available for many wells. For this study, we purchased digital well logs for 43 wells in the area. These well logs are described in more detail in Section 4.

2.4 Internal Government Reports

The acquisition and interpretation of the geophysical well logs for PVU Injection Well #1 are described in a series of reports prepared by consultants under contract to Reclamation (Dewan 1987a, 1987b, 1987c, 1988). The information contained in these reports is summarized and discussed in Section 4.1. Additionally, geologic well logs were provided as an attachment to a report by Clarence Harr (1988). The formation tops from Harr (1988) were also included in the GIS database and the tables in Appendix A.

2.5 Rasmussen Database

Don Rasmussen of Paradox Basin Data maintains a database of formation tops in the Paradox Basin, which he has obtained from extensive study of the available well log data. Formation tops from this database were purchased for 78 wells. These formation tops are included in the tables in Appendix A, but were not used in the GIS database.

2.6 Well log correlation

The seismic interpreter on this project, John Arestad at International Reservoir Technologies (IRT), and David List, a structural geologist currently consulting for IRT, used well log correlation to add or improve formation tops for a number of wells for which we had sonic logs. Gamma ray and density logs were also used for the correlations where available. These formation tops are included in the tables in Appendix A, but were not used in the GIS database.

3 GIS Database Details

A GIS database is maintained as an ArcGIS shapefile called Wells_25km.shp. This shapefile contains all known oil and gas wells within 25 km of the AOI and with depths of at least 6000 feet, which currently consists of 364 wells. The shapefile is in a NAD 83 UTM Zone 13N coordinate system and contains the following fields:

WELL_NAME: Official name of the well, from either the COGCC or UTDOGM databases.
LAT: Latitude, in decimal degrees.
LONG: Longitude, in decimal degrees
GRD_ELEV: Ground elevation at the location of the wellhead, in feet above sea level. This value was determined using the value of the raster file elev_sp_nad83 at the location of the wellhead.
OPERATOR: Well operator.
DATE: Well completion date for Utah wells. For Colorado wells, date may represent either well completion or spud date.
TOT_DEPTH: Total depth of the well, in feet.
VERT_DEPTH: Vertical depth of the well, in feet.
STATE: State in which the well is located.
COUNTY: County in which the well is located.
API: API Well number. This is a number that uniquely and permanently identifies the well, and is an industry standard developed by the American Petroleum Institute.
SONIC_RAST: 'A' indicates that a raster image of a sonic log is available; 'U' indicates that it is not, to our knowledge. As all of these raster images are available for free public download from the COGCC, those that Reclamation has acquired have not been distinguished.
SONIC_DIG: 'Y' indicates that the Bureau of Reclamation has acquired a copy of the digital sonic log in LAS format. 'A' indicates that a digital (typically LAS) file of a sonic log is available for purchase; 'U' indicates that it is not, to our knowledge.
SONIC_SRC: The source of digital sonic logs, if they have been acquired by Reclamation; otherwise the source of raster sonic logs. When the source is listed as "IHS", in some cases a raster file may also be available from the COGCC.
LEAD_DEP: The depth to the top of the Leadville formation, in feet, relative to the local ground surface. Some formation records refer to the "Mississippian" formation; this is assumed to be the Leadville formation. A value of -99 indicates that the depth is unknown.
LEAD_THICK: The thickness of the Leadville formation, in feet. This value was obtained by subtracting the depth to the top of the Leadville formation from the depth to the top of the Ouray formation. In some cases, the depth to the Ouray formation was not recorded but depths to other underlying formations were. The

thickness of the Leadville was not calculated in these instances, as it was not clear whether the stratigraphy varied in these locations or whether the formation record was incomplete. A value of -99 indicates that the thickness is unknown.
LEAD_SRC: The source of information about the depth to the Leadville formation. See Section 2 for description of sources.
PARA_DEP: The depth to the top of the Paradox salt, in feet. A value of -99 indicates that the depth is unknown.
PARA_SRC: The source of information about the depth to the Paradox formation. See Section 2 for description of sources.
BASE_FORMT: The deepest formation that was logged. In some cases this may not be the formation that is at the bottom of the well, if the formation log is incomplete. A value of “UNK” indicates that no formation log is available.
LEAD_ELEV: The elevation of the top of the Leadville formation, in feet above sea level. This value was obtained by subtracting the value of LEAD_DEP from the value of the elevation from the file elev_sp_nad83 at that point, assuming that the well is vertical. A value of -99 indicates that the elevation is unknown.
PARA_ELEV: The elevation of the top of the Paradox salt, in feet above sea level. This value was obtained by subtracting the value of PARA_DEP from the value of the elevation from the file elev_sp_nad83 at that point, assuming that the well is vertical. A value of -99 indicates that the elevation is unknown.
PHASE: The Phase of seismic data interpretation in which well logs from this well were provided to the seismic data interpreter. Note that Phase I well logs were also used in the Phase II interpretation. The most common reason for excluding wells from being used in the seismic interpretation is that relevant types of well logs were unavailable. Others were excluded due to being located far from seismic lines and/or having a total depth that was shallower than the top of the Paradox salt.

A map of all wells in the database is shown in Figure 3-1. Figure 3-2 through Figure 3-4 show the values of the Paradox elevation, Leadville elevation, and Leadville thickness fields, with surfaces interpolated from those fields. Due to the structural complexity, the large offsets across some faults, and the sparseness of well log data, the interpolated surfaces show only general trends and do not accurately represent the structural surfaces. Please refer to Arestad (2016; 2017) for more detailed surfaces developed from the seismic reflection data.

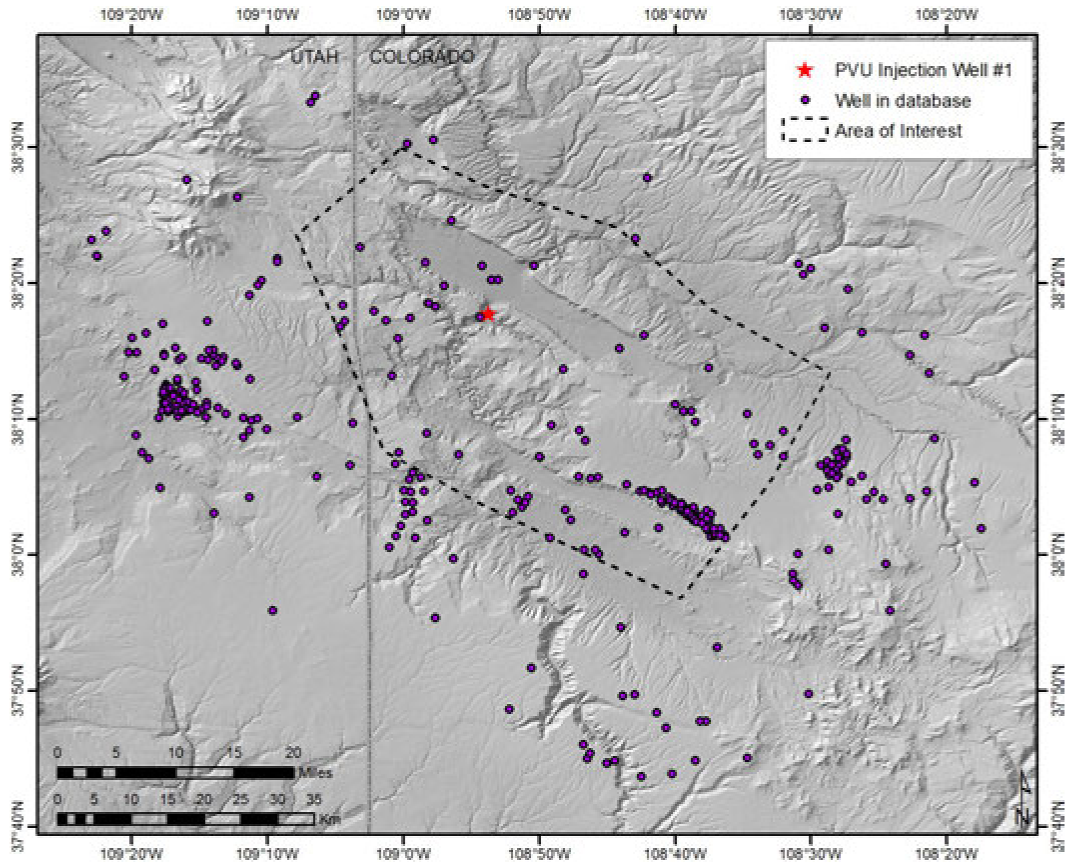

Figure 3-1. All wells in the GIS database. Dashed line outlines the area of interest (AOI).

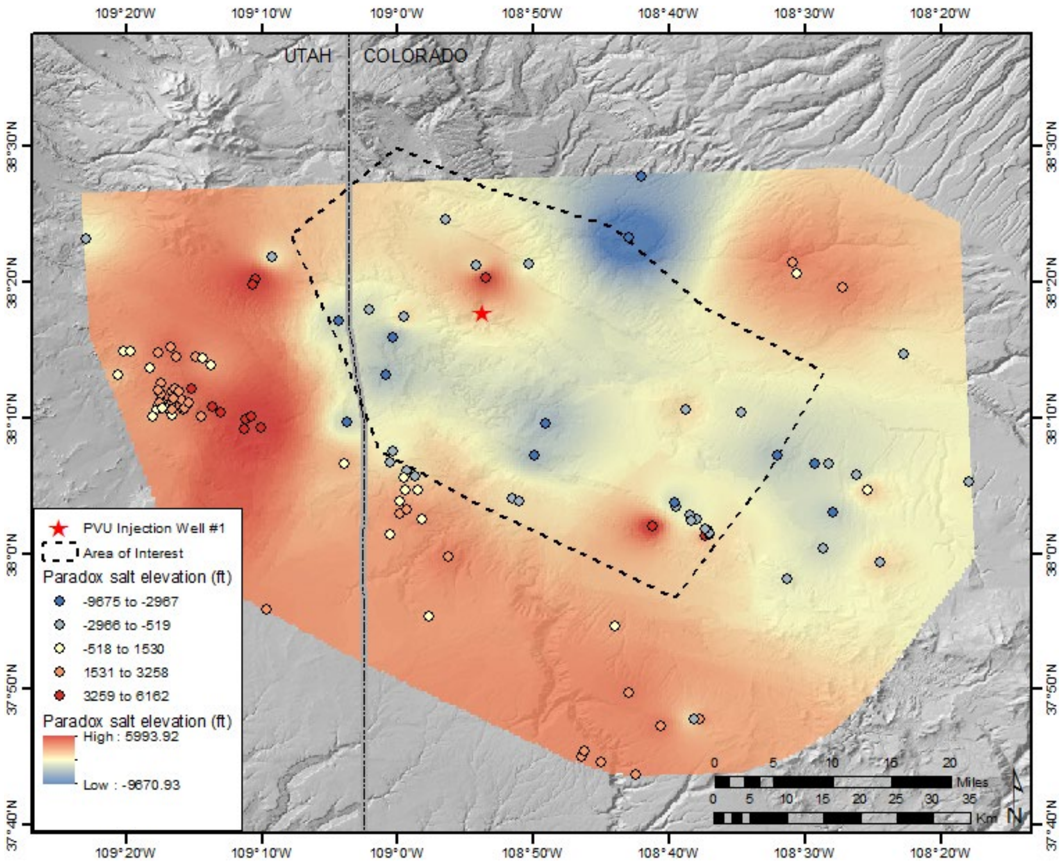

Figure 3-2. Wells with elevations to the top of the Paradox salt, and a surface interpolated from those elevations using Inverse Distance Weighting (IDW) interpolation. Surface is partially transparent to view topography beneath. Elevations are calculated by subtracting the depth to the Paradox salt from the ground surface elevation at the well's location, assuming a vertical well. Dashed line outlines the area of interest (AOI).

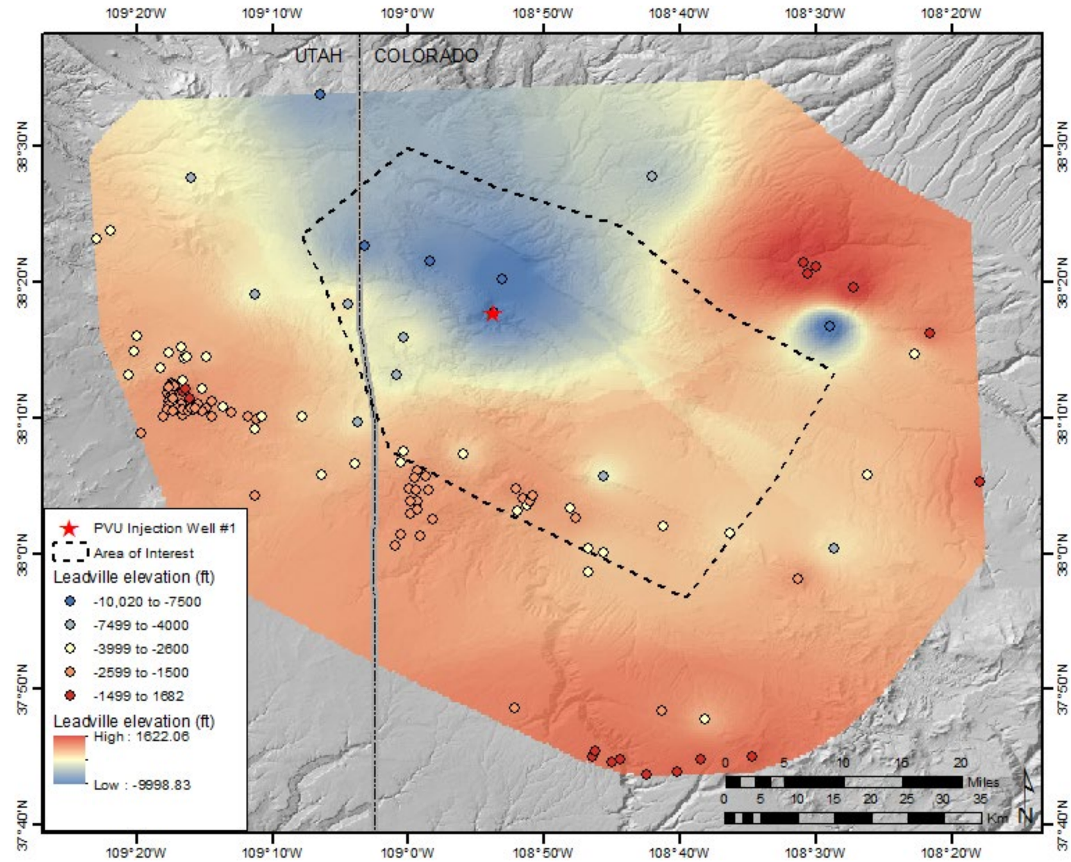

Figure 3-3. Wells with elevations to the top of the Leadville formation, and a surface interpolated from those elevations using Inverse Distance Weighting (IDW) interpolation. Surface is partially transparent to view topography beneath. Elevations are calculated by subtracting the depth to the Leadville formation from the ground surface elevation at the well's location, assuming a vertical well. Dashed line outlines the area of interest (AOI).

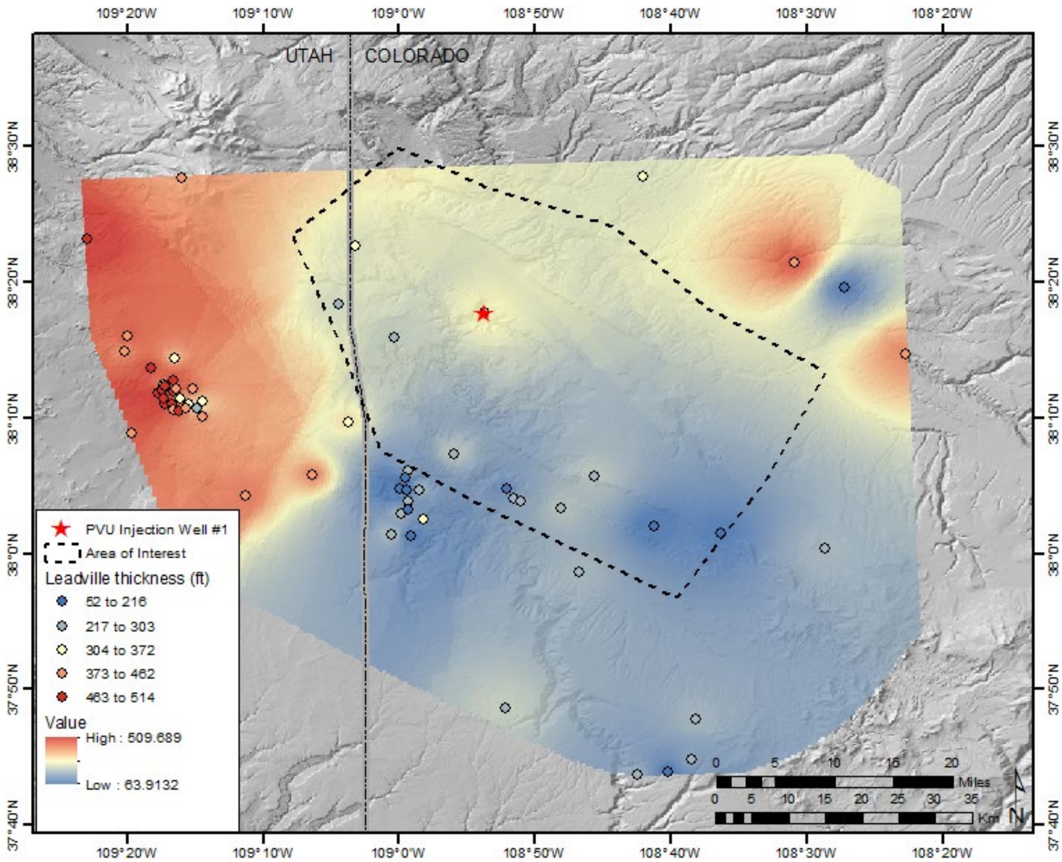

Figure 3-4. Wells with thicknesses of the Leadville formation and a surface interpolated from those elevations using Inverse Distance Weighting (IDW) interpolation. Surface is partially transparent to view topography beneath. Thicknesses are calculated by subtracting the depth to the Leadville formation from the depth to the Ouray formation. Dashed line outlines the area of interest (AOI).

4 Well log data

4.1 Well logs from PVU Injection Well #1

Initial well logging of PVU Injection Well #1 was conducted in 1987. Logging of the surface hole, from 2,012’-90’ depth, was performed on 1/14/1987 (Dewan, 1987a). There were two logging runs. The first run included a dual induction log, spherically-focused log, self-potential (SP) log, and natural gamma ray log. The second run included a borehole-compensated sonic (BHC-sonic) log, a natural gamma ray log, and caliper log.

Logging of the intermediate hole, from 14,050’-2,020’ depth, was conducted from 6/9/1987 to 6/12/1987 (Dewan, 1987b). There were four logging runs in this interval. Run 1 consisted of a dual laterolog (DLL), natural gamma ray log, micro-spherically focused log (MSFL), and dual caliper log. Run 2 consisted of a BHC-sonic log, 3-arm sonic caliper, and natural gamma ray log. Run 3 consisted of a digital sonic (SDT) log and natural gamma ray log. Run 4 consisted of a stratigraphic high-resolution dipmeter (SHDT) log and natural gamma ray log.

Logging of the liner hole, from 15,950’-14,050’ depth, was conducted from 8/4/1987 to 8/18/1987 (Dewan, 1987c). Logs included a dual laterolog (DLL), micro-spherically focused log (MSFL), litho-density and compensated neutron-gamma ray log, spectral gamma ray log, digital sonic (SDT) log, borehole televiewer log, dipmeter log, formation microscanner log, geochemical log, and natural gamma ray log. Four interpreted logs were also provided for the liner hole, including a mechanical properties log, fracture identification log (FIL), directional survey, and elemental analysis (ELAN) log. Additionally, a geological supervision of drilling log was provided, along with a true vertical depth log that includes P-wave slowness, sonic-derived porosity, natural gamma ray, and caliper logs. Both of these logs are described in the final geologic well report (Harr, 1988).

Table 1 lists the types of well logs that were performed and their depth intervals. For many of the PVU Injection Well #1 logs, only a single paper copy of the log existed. In order to better utilize the information provided by these logs and to ensure their availability in the future, we had all the paper well logs scanned. Some well logs were available for purchase from IHS. These logs included the spectral gamma ray log (#11 in Table 1), sonic logs with slowness-time coherence (STC) processing for the liner hole and a portion of the intermediate hole (#18, #26). We purchased these digital well logs, as it was more cost-effective than digitizing the scanned images. The remaining logs were digitized by LogDigi. We had all of the logs scanned, while only the final logs that could be represented as an LAS-format log were digitized. In some cases the final logs are simply copies of the field prints, while in other cases they have been edited – for example, eliminating bad logging runs and changing the horizontal scale.

One log is currently missing: the raw data from the directional survey (#29). We do, however, have a final print of the interpreted directional survey (#33). The final print also includes a table of the azimuths and deviations; thus, the missing print is not believed to contain any substantial additional data.

Temperature logs were conducted in 1989, 1990, and 1992, along with spinner surveys in 1990 and 1992 and a radioactive tracer survey in 1990, to determine which formations were accepting fluid. These logs were also scanned, but they are not included in Table 1, as they are not considered to be part of the initial set of logging. The spinner surveys were strongly affected by the magnetic markers in the liner tubes, and were therefore of less value than the radioactive tracer survey (Brown and Anderson, 1990).

Table 1. PVU well logs. Each entry in the table represents a single paper well log. All of these logs have been scanned into raster format, and many have also been digitized into LAS format, as indicated in the last column.

#	Type	Depth range (ft)[1]	Depth interval (ft)[1]	Scanned	Digitized
1	Dual induction-SFL-SP-GR	2,012 - 90	1,922	Y	N
2	BHC Sonic - GR - Caliper	2,012 - 90	1,922	Y	N
3	Dual Laterolog/MSFL	14,057 - 1,800	12,257	Y	N
4	BHC Sonic - GR - Caliper	14,055 - 1,800	12,255	Y	Y
5	Digital sonic waveforms	14,057 - 12,986	1,071	Y	N
6	Dipmeter raw data	14,058 - 1,900	12,158	Y	N
6a	4-arm caliper	10,700 - 9,696	1,004	Y	Y
7	Dual Laterolog (DLL) & micro-spherically focused log (MSFL)	15,939 – 14,043	1,896	Y	N
8	Digital sonic log	15,954 – 14,043	1,911	Y	N
9	Stratigraphic dipmeter data	15,952 – 14,080	1,872	Y	N
10	Litho-density & compensated neutron-gamma ray log	15,968 – 14,043	1,925	Y	N
11	Spectral gamma ray	15,935 – 14,043	1,892	Y	Y
12	Formation microscanner data	15,732 – 14,070	1,662	Y	N
13	Borehole televiewer	15,945 – 14,043	1,902	Y	N
14	Geochemical logging tool	15,870 – 14,043	1,827	Y	N
15	Dual induction - SFL	2,012 - 90	1,922	Y	Y
16	Dual Laterolog (DLL) & micro-spherically focused log (MSFL)	15,940 – 1,800	14,140	Y	Y
17	Dual Laterolog/MSFL	2,012 - 90	1,922	Y	N

#	Type	Depth range (ft)[1]	Depth interval (ft)[1]	Scanned	Digitized
18	Digital sonic waveforms with STC processing	15,950 - 12,990	2,960	Y	Y
19	Dipmeter raw data	15,950 - 1,900	14,050	Y	Y
20	Litho-density/compensated neutron	15,968 – 14,043	1,925	Y	Y
21	Natural gamma ray spectrometry	15,935 – 14,043	1,892	Y	Y
22	Formation microscanner data	15,732 – 14,070	1,662	Y	Y
23	Unnormalized borehole televiewer	15,945 – 14,043	1,902	Y	N
24	Geochemical logging tool	15,870 – 14,043	1,827	Y	Y
25	GST Quality control	15,870 – 14,043	1,827	Y	Y
26	STCO - Slowness time coherence	14,057 - 12,986	1,071	Y	N
27	Mechanical properties	15,925 - 14,050	1,875	Y	Y
28	MSD (Mean square dip)	14,058 - 1,900	12,158	Y	N
29	Directional survey	15,950 – 1,920[2]	14,030[2]	N	N
30	Waveform analysis - STC processing	15,954 – 14,043	1,911	Y	Y
31	Mechanical properties	15,925 - 14,050	1,875	Y	Y
32	MSD (Mean square dip)	15,952 – 14,080	1,872	Y	N
33	Directional survey	15,950 – 1,920	14,030	Y	N
34	FIL (Fracture identification log)	15,950 - 14,080	1,870	Y	Y
35	ELAN (Geochemical log)	15,930 - 14,050	1,880	Y	Y
36a	Formation microscanner	15,720 - 15,515	205	Y	N
36b	Formation microscanner	14,320 - 14,090	230	Y	N
36c	Formation microscanner	14,320 - 14,090	230	Y	N
36d	Formation microscanner	15,730 - 15,508	222	Y	N
37	Sonic porosity - STC processing (Dolomite scale)	15,954 – 14,043	1,911	Y	Y
E1	True vertical depth log	15,971 - 90	15,881	Y	Y
E2	Geological supervision of drilling	16,000 - 9,990	6,010	Y	N

[1]The depth range represents the minimum and maximum depths of any logs displayed on the print; some logs may not extend the entire depth range.
[2]The depth range and depth interval of the raw data from the directional survey were inferred from the final print (#33); Reclamation is not in possession of this log to verify these values.

Temperature logging was also performed in 1993, 1994, and 2001, as well as caliper logging in 2001 (Subsurface Technology, 2001), but we are not currently in possession of those logs.

4.1.1 Types of logs and their purposes

4.1.1.1 Gamma Ray Logs

Gamma ray logging (#1, #2, #4 in Table 1) is used to measure the natural emission of gamma rays by a formation. Gamma ray logging can be used to characterize lithology. Some lithology types, such as shales, tend to have higher natural radioactivity, while sandstones tend to have lower natural radioactivity. Salt generally has very low radioactivity. Gamma ray signatures are also useful to correlate formations between wells.

One variant on gamma ray logging is spectral gamma ray logging (#11, #21). In addition to measuring the total gamma ray count, spectral gamma ray devices can also sort the pulses into bins by their size, and a spectrum equivalent to the energy spectrum of the incoming gamma rays is produced. The energy of the gamma rays is determined by which element emitted them (potassium, thorium, or uranium). The most common application for spectral gamma ray curves is clay typing. Spectral gamma rays can also be used to evaluate stimulations and completions, in combination with radioactive tracers (petrowiki.org).

In PVU Injection Well #1, the quality of both the standard gamma ray and spectral gamma ray curves were good (Dewan, 1987b; Dewan, 1987c).

4.1.1.2 Geochemical Logs

Geochemical logs (#14, #24, #25) record responses from Al, Si, Ca, S, Fe, Cl, H, K, Th, and U by nuclear means (Dewan, 1988). The most common applications are in rock and clay typing for reservoir description. However, uncertainties are relatively large, and element-to-mineral mapping is not unique, so a limited suite of minerals must be selected before analyzing the data to provide meaningful results (petrowiki.org).

In PVU Injection Well #1, the quality of these logs was reasonably good. However, the Al log was invalid due to inadvertently running it with incorrect source-detector spacing.

An elemental analysis (ELAN) log (#35) was calculated from the geochemical log, in conjunction with the density and neutron logs. This log shows the volumetric mineral percentages of six pre-determined minerals.

4.1.1.3 Density and Neutron Logs

Density logs (#10, #20) send gamma rays into a formation and detect those that are scattered back. They take two measurements at differing locations from the source, and bulk density can be calculated from these two measurements (petrowiki.org). Density logs can be used to correlate formations between wells. They can also be used to calculate porosity logs.

A related type of log is a neutron log. Neutron logs emit neutrons from a source and detect those that are scattered back. One common type of neutron log is a compensated neutron log (CNL) (#10, #20). Like density logs, neutron logs can be used to calculate formation porosity.

The quality of both of these logs were substandard in the liner hole of PVU Injection Well #1, due to washouts and borehole eccentricity (Dewan, 1988).

In the intermediate hole, a density log was not run, but a synthetic density log was computed from the sonic log as:

$$\rho = 1.63 + 52.8 / t \qquad (4.1)$$

below 9300 feet and

$$\rho = 1.61 + 57.2 / t \qquad (4.2)$$

above 9300 feet, where ρ is density in gm/cm^3 and t is compressional travel time per unit distance (slowness) in µs/ft. These formulae do not accurately compute the density of salt, so the density of the salt zones, picked as those zones having both resistivities greater than 20,000 ohm-m and slownesses greater than 54 µs/ft, was taken to be 2.16 gm/cm^3 (Dewan, 1987b).

4.1.1.4 Sonic Logs

Sonic logs, also known as acoustic logs, (#2, #4, #8 in Table 1) measure P-wave travel time versus depth. One common use of sonic logs is to aid in the interpretation of seismic reflection data, in particular, to compute synthetic seismograms to tie seismic reflectors to lithology. Sonic logs can also be used to calculate porosities, using various assumptions about the lithology. Velocity (or its inverse, slowness) can also be used to correlate formations between wells, especially in conjunction with other log types. Salt is particularly easy to identify on sonic logs, having a consistent velocity of about 14,000 ft/sec, or equivalently, a slowness of about 70 µs/ft.

Some sonic logging tools can measure the full waveform, allowing for the travel-times of S-waves and Stoneley waves to be determined (#5). This is less routine, especially for older logs, but was performed in the logging of PVU Injection Well #1 over a limited depth range. One common type of processing for these types of logs is slowness-time coherence (abbreviated as STC or STCO) processing (#18, #26, #30), which allows packets of energy to be identified.

In PVU Injection Well #1, the compressional-wave and shear-wave travel times obtained from the sonic log were very good, except in a few washed-out intervals, while the Stoneley-wave values were more questionable (Dewan, 1988).

Sonic logs can indicate fractured zones, which tend to show up as zones where the shear-wave amplitude is depressed relative to the compressional-wave amplitude. However, this effect is not a unique indication of fractures, as borehole roughness and out-of-roundness can also depress amplitudes. Hence, interpretation of fractured zones from sonic logs should be considered in conjunction with other fracture indicator logs (Dewan, 1988).

Sonic logs can also be used to calculate porosity, using various assumptions about the lithology. For PVU Injection Well #1, a sonic-derived porosity curve for the intermediate hole was calculated using the formula

$$\phi = 0.625(1 - t_{ma} / t) \tag{4.3}$$

where t is the sonic travel time in µs/ft and t_{ma} is the matrix travel time. A value of 49 µs/ft was assumed for t_{ma}, which is appropriate for limestone (Dewan, 1987b). This curve was displayed on the sonic log (#4).

A sonic-derived porosity for the liner hole (#37) was calculated using the Wyllie relation:

$$\phi = (t - t_{ma}) / (t_f - t_{ma}) \tag{4.4}$$

where t_f is the fluid travel time, taken to be 190 µs/ft and t_{ma} is the matrix travel time, taken to be 47.6 µs/ft, which is also said to be appropriate for limestone (Dewan, 1988). The reason for the difference in formulae is not explained.

A mechanical properties log (#27, #31) was also calculated from the sonic and density logs (for the intermediate hole, a density log was not recorded, so the synthetic densities discussed in section 4.1.1.3 were used instead). This log included calculations of Poisson's ratio, the minimum horizontal pressure, fracture pressure, pore pressure, and overburden pressure. Poisson's ratio, μ, was calculated as:

$$\mu = 0.5(r^2 - 2) / (r^2 - 1) \tag{4.5}$$

where $r = t_s / t_c$, the ratio of shear to compressional travel times.

The overburden pressure P_O was calculated by integrating the density log, as:

$$P_O(z) = .433 \int^{z} \rho(z) dz \tag{4.6}$$

where z is depth in feet, ρ is density in gm/cm^3 (measured or synthetic, with the measured densities limited to a minimum value of 2.4 gm/cm^3 whenever it fell below that value due to washouts) and the overburden pressure is in psi. An extra 1000' of overburden was added with density of 2.4 gm/cm^3 to account for the fact that the well deviation caused it to bottom underneath cliffs that extended about 1,000 ft above the rig floor (Dewan, 1987b; Dewan, 1988).

Pore pressure P_P was calculated as:

$$P_P(z) = .442 \int^{z} dz \tag{4.7}$$

where z is depth in feet and the pore pressure is in psi.

Fracture closure pressure, FP_{CL}, in psi, was calculated as:

$$FP_{CL} = mP_O + P_P(1 - m) \tag{4.8}$$

where $m = \mu / (1 - \mu)$. Fracture initiation pressure, FP_{IN}, in psi, was calculated as

$$FP_{IN} = 2FP_{CL} - P_P \tag{4.9}$$

Fracture closure pressure was also recalculated with tensile strength included, as:

$$FP_{INW} = FP_{IN} + S_t \tag{4.10}$$

where S_t is the tensile strength given by:

$$72.3 \times 10^{-10} K \left(0.0045E\left(1 - Vcl\right) + 0.0080E * Vcl\right). \tag{4.11}$$

Vcl is the fraction of clay determined from the gamma ray log, and the bulk modulus K and Young's modulus E are given by the following formulae:

$$K = 1.34 * 10^{10} \rho (1 / t_c^{\ 2} - 1.33 / t_s^{\ 2}) \tag{4.12}$$

$$E = 2.68 * 10^{10} \rho (1 + \mu) / t_s^{\ 2} \tag{4.13}$$

where t_c and t_s are the compressional-wave and shear-wave travel times (slownesses), respectively. According to Dewan (1988), the tensile strength increases fracture initiation pressure but its calculation is of dubious reliability, so the fracture pressures that disregard tensile strength are more reliable.

4.1.1.5 Resistivity and Spontaneous Potential Logs

Resistivity logging measures the formation resistivities. They are often recorded in conjunction with the formation spontaneous potential, or SP. The resistivity of a formation depends on the resistivity of the formation water, the amount of water present, and the structure and geometry of the pores (petrowiki.org). There are a number of different types of resistivity logs, each created to provide optimal measurements under a particular set of subsurface conditions. The types used in the logging of PVU Injection Well #1 include spherically focused logs (SFL) (#1, #15), dual laterologs (DLL) (#3, #16, #17), and dual induction logs (#1, #15). A dual laterolog consists of shallow laterolog (LLS) and deep laterolog (LLD) curves, which differ in their depths of investigation. Similarly, dual induction logs produce measurements for two depths of investigation. Data from multiple depths of investigation can be used to determine the resistivity of the virgin formations beyond the near-wellbore zone that has been invaded by drilling fluids.

Microresistivity logs, such as micro spherically focused logs (MSFL) (#3, #7, #16, #17), are a subset of resistivity logs that can detect permeability intervals on a fine vertical scale. They are useful for the qualitative evaluation of permeability, but do not measure permeability quantitatively.

The SP curve (#1) records the electrical potential differences generated by the interaction of formation water, conductive drilling fluid, and ion-selective shales. Its applications include differentiating potentially porous and permeable reservoir rocks from impermeable clays and shales, defining bed boundaries, correlating nearby wells, indicating the shaliness of shaly formations, and estimating formation-water resistivity.

Resistivity logs can also be used to calculate porosity. In PVU Injection Well #1, a porosity was calculated from the deep resistivity curve using the formula:

$$\phi = 0.15 / \sqrt{R_{LLD}} \qquad (4.14)$$

where ϕ is porosity and R_{LLD} is the resistivity measured from the deep laterolog, in ohm-meters. The shallow laterolog and MSFL curves were judged to be unreliable (Dewan, 1988).

Salinity was calculated from the SP log to be 50,000 ppm, assuming the only ions in the water were from NaCl.

4.1.1.6 Borehole Televiewer and Formation Microscanner Logs

Borehole televiewer (BHTV) and formation microscanner (FMS) logs both provide images of the borehole wall. BHTV devices (#13, #23) use an ultrasonic transducer, whereas FMS devices (#12, #22, #36) use microresistivity. The images can be used to identify fractures, borehole breakouts, and other borehole features.

In PVU Injection Well #1, according to Dewan (1988), the BHTV provided little useful information, particularly because the ellipticity of the borehole created large amplitude variations that obscured fracture and vug indications. However, the BHTV was later used to analyze borehole breakouts in order to determine the direction of maximum horizontal stress, in conjunction with the dipmeter log (Hickman, 2003). The FMS provided good quality data (Dewan, 1988).

4.1.1.7 Caliper Logs

Caliper logs measure the borehole diameter. Since boreholes are rarely a perfect circle, calipers with multiple arms are necessary to accurately capture the size and shape of the borehole. The most common are three-arm (#2, #4), four-arm (#6a), and six-arm calipers.

Four-arm and six-arm calipers can be used to detect borehole breakouts and drilling-induced fractures, the orientations of which are determined by the horizontal stress direction. Borehole breakouts will be approximately perpendicular to the maximum horizontal stress, while drilling-induced fractures will be approximately parallel to the maximum horizontal stress.

In PVU Injection Well #1, the calipers show clear eccentricity of the borehole (Dewan, 1988). However, there are some uncertainties in the caliper orientation that limit its value in interpreting the stress direction.

4.1.1.8 Directional Surveys

A directional survey (#29, #33) is a series of measurements of borehole inclination and direction. From these measurements, the 3D trajectory of the well, including the bottomhole location, can be determined.

A true vertical depth (TVD) log (E1) is a plot of the true vertical depth vs. measured depth, calculated from the directional survey. For wells that are not perfectly vertical, the measured depth will be greater than the vertical depth.

The quality of the directional survey in PVU Injection Well #1 was good; however, it was only run from 1,920 ft to total depth (Dewan, 1988), so there is still some uncertainty in the bottomhole location.

4.1.1.9 Dipmeter Logs

A dipmeter (#6, #9, #19) measures the resistivity at three or more different points on the borehole, which can be correlated to define dipping planes. The magnitude and direction of the dipping bedding planes can be used as part of a complete geologic description of the formations crossed by the borehole.

The mean square dip (MSD) (#28, #32) is a method of computing a weighted average of all the pad-to-pad dips, which is used for structural or regional dip analysis (Crain, 2016).

The quality of the dipmeter logs was good in PVU Injection Well #1 below about 10,500 ft, except for approximately 430 ft where the tool had to be closed to avoid repeated hang-ups (Dewan, 1987b; Dewan, 1988). One of the pads was torn off during logging at approximately 10,500 ft, leading to unreliable readings in the shallower section of the borehole (Dewan, 1987b).

A Fracture Identification Log (FIL) (#34) was obtained from the dipmeter log by overlaying the conductivities derived from adjacent pads of the dipmeter. In theory, the fracture anomalies will not overlay on curves from adjacent pads, whereas horizontal bedding anomalies will (Dewan, 1988).

4.2 Well logs from other wells in the region

Digital well logs were obtained from 90 wells. The well log data were divided into Phase I and Phase II data, in parallel with the phases of the seismic reflection data licensing, processing, and interpretation. The Phase I well logs are those that were used in the interpretation of the seven Phase I seismic reflection lines, while the Phase II data were only used for the processing of the Phase II seismic reflection lines (Figure 4-1).

For wells other than PVU Injection Well #1, the primary logs of interest were sonic, gamma ray, and neutron density logs. These types of logs are commonly available and are useful for structural interpretation, both on their own—by interpolating them to create a low-resolution structural model—and in conjunction with seismic reflection data. Other types of logs were sometimes obtained as needed.

There are 41 well logs in Phase I, including the PVU Injection Well #1, and 49 well logs in Phase II. Information is also provided for an additional 81 wells for which the Bureau of Reclamation is not in possession of well logs, for a total of 171 wells. In some cases, well logs are not available; in others, we chose not to purchase them. Information about these wells is provided in Table A-1. No entry in the “Phase” field indicates that the Bureau of Reclamation does not possess any digital logs for this well. The additional wells were included because formation tops were available from one or more sources, typically from the COGCC. One should use care in making interpretations from these formation tops, as they have not been verified.

Available formation tops for all 171 wells are provided in Table A-2 and Table A-3. Table A-2 contains the shallower formations, from the Dakota to the Cutler, while Table A-3 contains the deeper formations, from the White Rim sandstone to the Precambrian basement. These tables include tops from five different sources. Tops marked as “CO” or “UT” are from the COGCC and UTDOGM databases, respectively. Those marked as “IRT” were determined by the seismic interpreter on this project, John Arestad at International Reservoir Technologies, and David List, a structural geologist currently consulting for IRT. Those marked “DR” were provided by Don Rasmussen of Paradox Data. Those marked “CH” were taken from the geologic well log of PVU Injection #1 by Clarence Harr, the project geologist (Harr, 1988). See Section 2 for more detailed descriptions of these sources.

Due to inconsistent naming conventions between operators, it was necessary to make some assumptions about the formation tops reported in the COGCC and UTDOGM databases in order to compile these tables. These assumptions are that (1) the term “Hermosa” refers to the Honaker Trail formation, (2) the terms “Paradox”, “Salt Wash” (used in the formation record of 05-113-06082), and “Pennsylvanian” (used in the formation record of 05-085-05032) all refer to the first main salt member of the Paradox formation, and (3) the terms “Redwall limestone (used in the formation record of 43-037-30923) and “Mississippian” both refer to the Mississippian-age Leadville formation.

Depths to the Paradox formation, from any source, are available for 71 of the 90 wells for which we have well logs and depths to the Leadville formation are available for 46 of these wells. Depths to the Precambrian basement are only available for 5 wells. The wells for which Reclamation does not have well logs provide reported depths to the Paradox formation in 15 additional wells and to the Leadville formation in 3 additional wells. However, we are unable to verify these tops without the well logs.

Well logs from all wells are shown in Appendix B. Appendix B contains images of all available sonic logs (primarily P-wave slownesses, but S-wave slownesses are included where available), gamma ray logs, neutron logs, and density logs. For one well, 05-113-06138, a sonic porosity log is available but a sonic log is not, so the porosity log is included instead, in a different color than the sonic logs. Note that the well log names are the original ones provided by operators. See Crain (2016) for a well log curve name alias table.

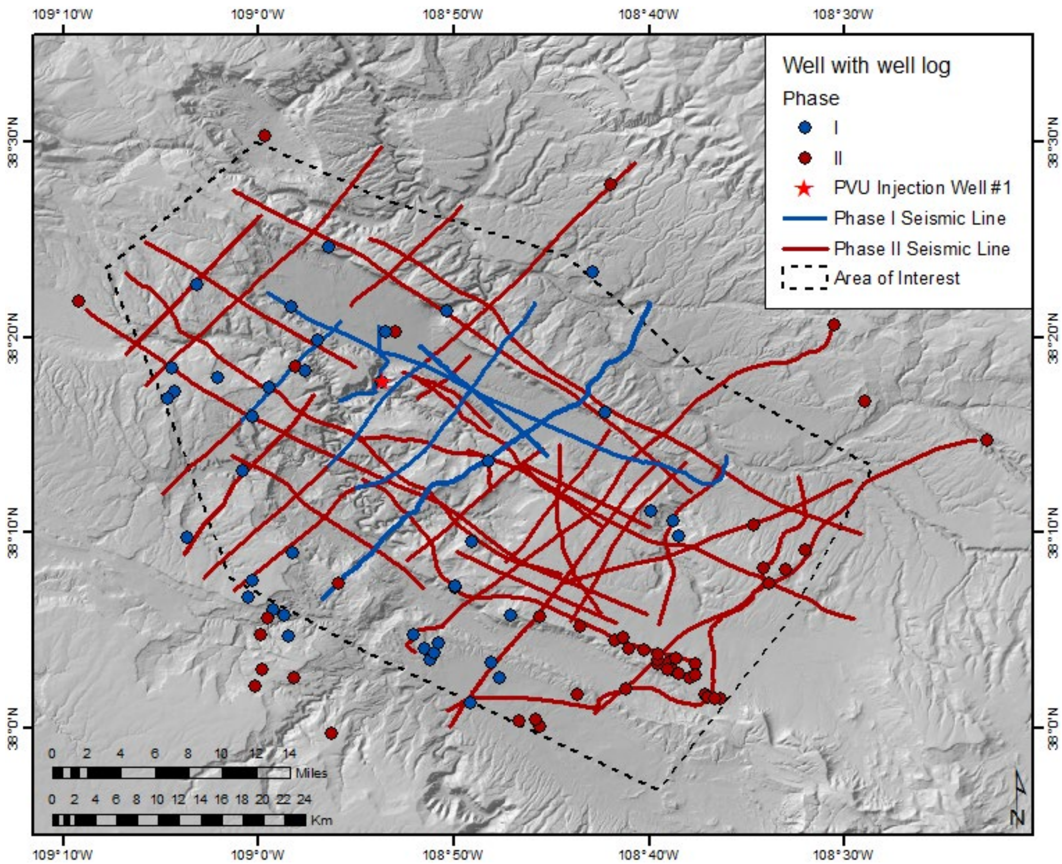

Figure 4-1. Locations of seismic reflection lines and wells with well logs.

4.2.1 Porosity analysis

The porosity of the Leadville formation is of significant interest in the siting of a second injection well, as the porosity influences the storage volume and the pressure response of the reservoir. Formation porosity can be estimated in multiple ways, including from analysis of core samples and well logs. Porosity can be calculated from density or neutron porosity logs, both of which use isotopic sources, resistivity logs, or sonic logs.

Calculating porosity from a sonic log is not the most accurate method of estimating the porosity; however, it is the method that can be used for the greatest number of wells in our area. Of the 29 wells for which depths to both the top and the bottom of the Leadville formation are available, we have sonic logs for 22 of these wells, while we only have neutron porosity logs for 3 wells and density logs for 6 wells. Porosity can be calculated from sonic travel times (slownesses) using the Wyllie equation,

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \tag{4.15}$$

where Δt is the measured acoustic transit time, Δt_{ma} is the acoustic transit time of the rock matrix, and Δt_f is the acoustic transit time of interstitial fluids (Wyllie et al., 1956).

Matrix slowness was assumed to be 47.6 µs/ft, which is appropriate for limestone, and fluid slowness was assumed to be 190 µs/ft. These values were taken from Dewan (1988). Bremkamp and Harr (1988) calculated sonic porosities using a value of 43.5 µs/ft, appropriate for dolomite, and thus calculated higher porosities. In reality, the Leadville has intervals of both limestone and dolomite (Harr, 1988), so no single value can accurately reflect the matrix velocity, and thus there is substantial uncertainty in the calculated porosity values. Bremkamp and Harr (1988) also calculated porosities for seven other wells in the area using the same value of matrix slowness. Five of these were located in the Lisbon Valley, a producing oil and gas field in Utah, which is outside our AOI. In this report we recalculated sonic porosity logs for all available wells in a consistent manner, so as to better identify any geographic trends.

Porosities were calculated for the entirety of the Leadville formation, from the top of the Leadville formation to the top of the Ouray formation, as reported in Table A-3. For wells where tops were available from multiple sources, the tops from the COGCC and UTDOGM databases were used preferentially where available, followed by the Rasmussen tops and then the tops obtained by IRT.

The calculated porosities are shown in Appendix C, along with the tops of the Leadville and Ouray formations and the sonic logs from which the porosity logs are calculated. Neutron porosity and density porosity logs are also shown for comparison where available. These logs are denoted as NPHI and DPHI, respectively, while SPHI indicates a sonic-derived porosity log. Note that while the porosity is shown for the entire interval for which a sonic log is available, the calculated porosities use values appropriate for limestone, and thus may not be accurate for other rock types.

The calculated values of sonic porosities are shown in Table 2. In addition to the average porosities, the number of feet with porosities greater than 3%, 5%, and 10% are shown, along with the number of porosity-feet (the product of average porosity and Leadville thickness). One well, 05-085-06002, has a calculated average porosity less than 0, which is obviously physically impossible, suggesting that the matrix slowness must be less than 47.6 µs/ft. In Table 2 and the figures that follow, the average porosity is presented as calculated, but the number of porosity feet is presented as 0 feet.

Figure 4-1 through Figure 4-4 show maps of the average porosity, number of feet with greater than 5% porosity, and porosity-feet, respectively. All three figures show significant variability of the Leadville porosities in the wells, even amongst closely-spaced wells. There is no obvious spatial trend in the porosity.

Figure 4-5 shows a scatter plot of average porosity of the Leadville formation versus the elevation of the tops of the Leadville formation. There appears to be a possible trend of higher average porosities in wells where the Leadville is shallower; however, this trend is fairly weak.

Table 2. Depth, thickness, and porosity of Leadville formation.

API	Lead. Depth (ft)	Lead. Thickness (ft)	Feet with >10% Poro.	Feet with >5% Poro.	Feet with >3% Poro.	Ave. Poro. (%)	Poro.-Ft
05-085-05014	9,376	420	11.0	78.5	197.0	3.2	13.5
05-085-05018	10,960	290	9.0	30.5	80.0	2.7	7.69
05-085-05111	13,984	416	1.5	7.5	36.0	0.77	3.20
05-085-06002	6,660	426	7.5	17.5	29.5	-0.05	0.00
05-085-06008	14,042	342	0.0	2.0	24.5	0.40	1.37
05-085-06033	15,430	314	5.5	10.0	10.5	0.95	2.98
05-113-05008	9,195	182	3.0	29.5	80.5	3.3	5.93
05-113-05009	9,150	189	0.0	15.5	56.5	2.1	3.97
05-113-05011	9,360	305	4.5	10.0	14.0	0.62	1.89
05-113-05012	9,050	266	12.0	57.0	95.0	3.0	8.01
05-113-05017	8,765	261	5.5	35.5	90.0	2.6	6.89
05-113-05019	9,920	565	63.5	101.5	161.5	2.7	15.0
05-113-05076	7,990	210	0.0	7.0	27.5	0.85	1.79
05-113-05077	8,900	280	4.5	31.0	65.5	2.2	6.02
05-113-06006	10,403	189	0.0	17.0	43.5	1.6	3.01
05-113-06013	9,250	382	5.0	16.0	51.5	1.5	5.58
05-113-06018	8,846	308	0.5	21.0	94.5	2.2	6.75
05-113-06041	7,900	224	2.0	12.5	45.5	2.0	4.44
05-113-06044	7,974	254	0.0	11.0	43.0	1.7	4.19
05-113-06062	8,516	282	0.5	61.0	114.0	2.9	8.18
05-113-06082	8,295	257	15.5	60.0	105.5	3.5	8.89
05-113-06106	8,761	236	0.0	6.0	33.0	0.92	2.17
05-113-06244	8,127	261	0.0	9.5	31.0	1.2	3.13
43-037-11191	11,340	303	0.0	0.0	13.0	0.90	2.73
43-037-11353	10,725	354	9.5	45.5	103.5	2.1	7.40
43-037-30923	12,168	405	103.5	156	202.5	5.9	23.8

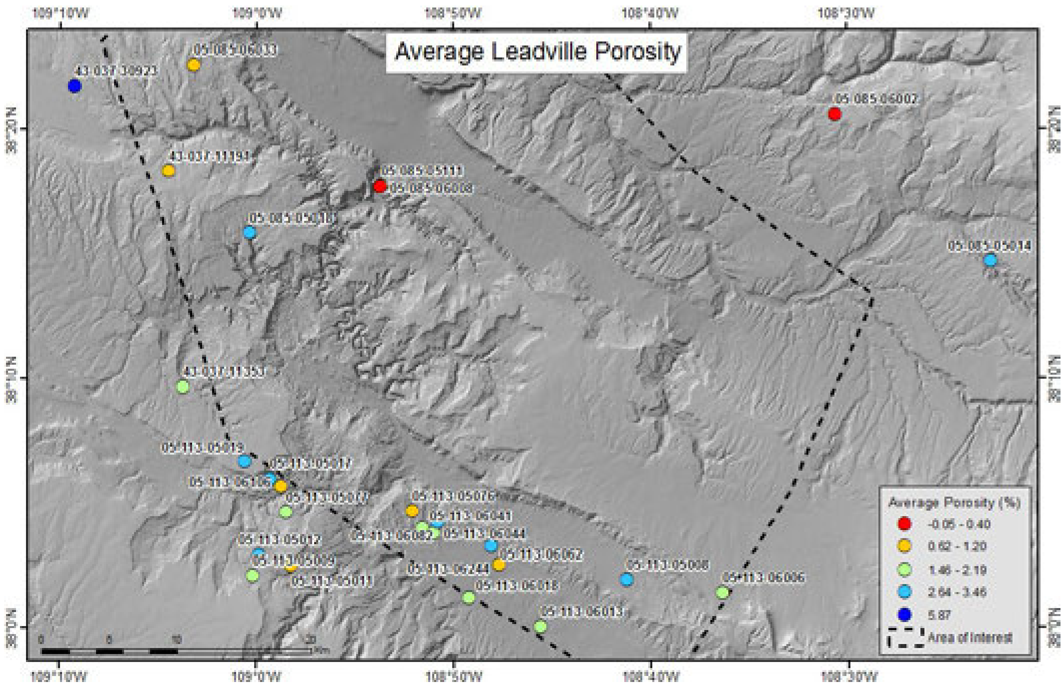

Figure 4-2. Average porosity of Leadville formation.

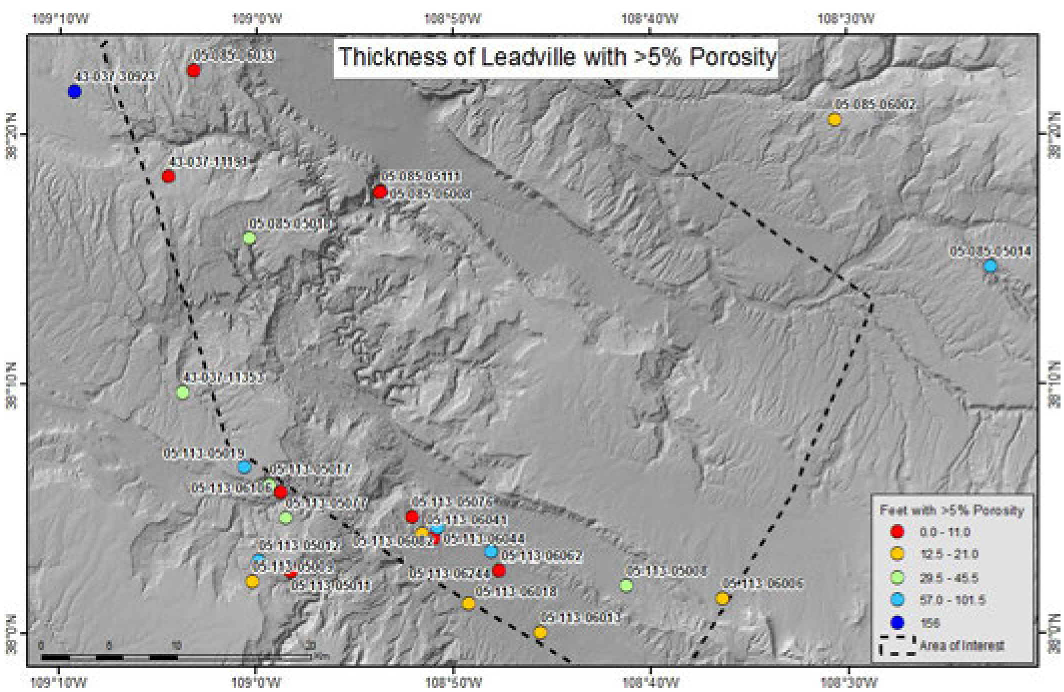

Figure 4-3. Thickness of Leadville formation with greater than 5% porosity.

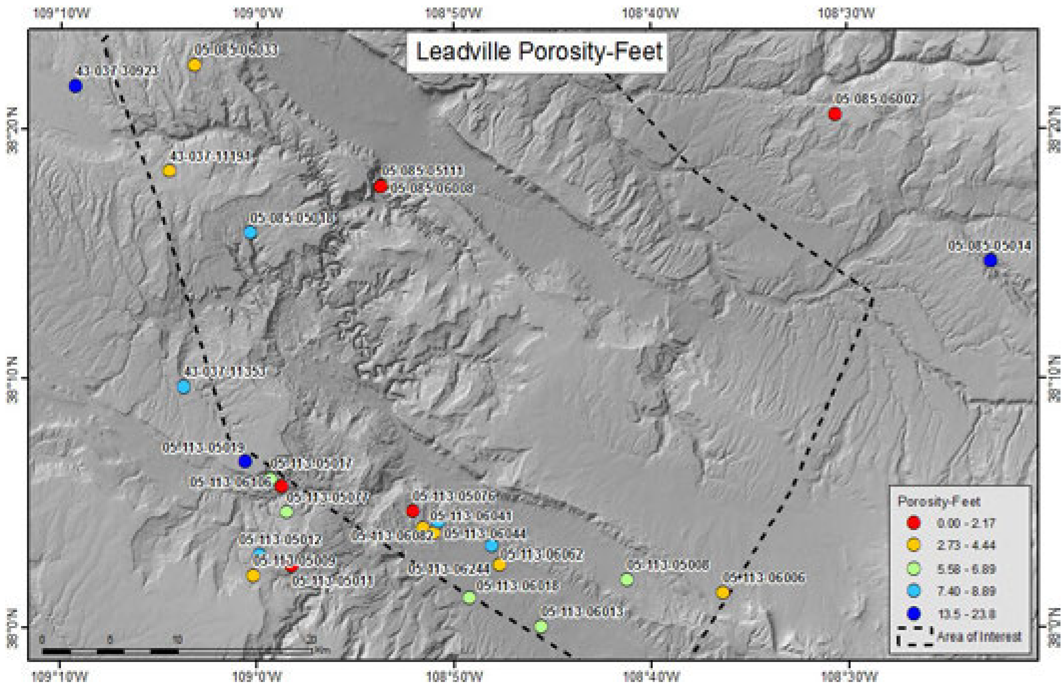

Figure 4-4. Porosity-feet of Leadville formation.

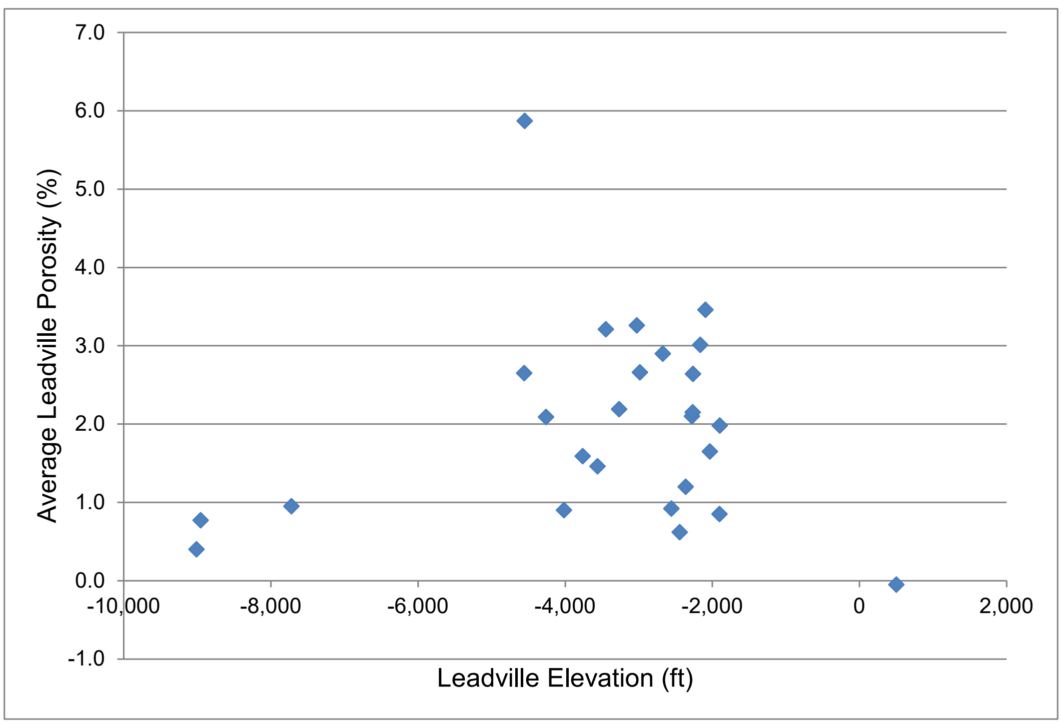

Figure 4-5. Average porosity of Leadville formation versus elevation of the top of the Leadville formation.

5 Summary

This report describes the efforts that were done to compile well data as part of the larger second well site investigations. The data sources utilized included the Colorado and Utah state databases, IHS Energy Lognet, internal government reports, a proprietary database compiled by Don Rasmussen, and well log correlations done by John Arestad and Dave List as part of the seismic reflection interpretation. These efforts included compiling a GIS database of 364 wells that are at least 6000' deep and within 25 km of our area of interest. Formation tops were also compiled for 171 wells, with 90 of those wells being used in the interpretation of the seismic reflection data. The efforts also included making the PVU well logs more accessible by scanning and digitizing the paper well logs and summarizing the information that was obtained from them.

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Appendix A: Tables of well information and formation tops

Tables A-2 and A-3 are not publicly available because they contain proprietary data licensed from private sources.

Table A-1: Well information. Elevations are those of the kelly bushing, unless otherwise specified (GL = ground level, DF = drill floor). Locations are taken from Don Rasmussen's database where available, as those locations have been verified using aerial photography when possible. Where unavailable, locations are taken from the COGCC or UTDOGM databases. See Section 4.2 for further details.

API	WELL_NAME	OPERATOR	LAT	LONG	ELEV (FT)	PHASE
05-077-07372	ALTEX-SINBAD 1	NORTH AMERICAN ROYALTIES INC	38.5044	-108.9950	5595	II
05-077-40018	HUSKY-HUBER #2	HUSKY OIL CO	38.5088	-108.9635	6347	
05-085-05011	COLORADO FEDERAL B 1	SKELLY OIL COMPANY	38.2231	-108.3544	6021	
05-085-05014	SAN MIGUEL UNIT # 2	UNION OIL COMPANY OF CALIFORNIA	38.2452	-108.3787	5929	II
05-085-05018	WRAY MESA UNIT 3	PURE OIL CO.	38.2646	-109.0065	6402	I
05-085-05021	AYERS #1	CHICAGO CORPORATION	38.2846	-108.9063	4986 (DF)	
05-085-05022	WRAY MESA UNIT 2	SHELL OIL COMPANY	38.2908	-108.9925	6956	I
05-085-05023	WRAY MESA UNIT 1	SHELL OIL COMPANY	38.3085	-108.9694	6539	II
05-085-05027	SCORUP SOMERVILLE WILCOX 1	CONTINENTAL OIL COMPANY	38.3371	-108.8842	5064	II
05-085-05028	WILCOX 2	GENERAL PETROLEUM CORPORATION	38.3544	-108.9035	5108 (GL)	
05-085-05032	URAVAN UNIT 1	HUMBLE OIL & REFINING COMPANY	38.3880	-108.7154	5849	I
05-085-05102	KIRBY-GOVERNMENT 1	DYER* J G	38.1762	-108.6479	5696	I
05-085-05108	COYOTE WASH UNIT 1	MIAMI OIL PROD INC	38.2192	-109.0151	5434	I
05-085-05111	PARADOX VALLEY UNIT INJECTION WELL 1	BUREAU OF RECLAMATION	38.2965	-108.8949	5027.7	I
05-085-06001	MONTROSE UNIT 1	UNION OIL COMPANY OF CALIFORNIA	38.1844	-108.6661	6825	I
05-085-06002	KIRBY GOVERNMENT #1	MIAMI OIL PROD INC	38.3436	-108.5094	7163	II
05-085-06003	MONTROSE UNIT-GOV 2	UNION OIL COMPANY OF CALIFORNIA	38.1761	-108.6562	6119	
05-085-06004	MONTROSE UNIT WELL 3	MOUNTAIN FUEL SUPPLY COMPANY	38.1635	-108.6413	6616.6	I
05-085-06006	MARTIN MESA 1 A 12	UNION OIL COMPANY OF CALIFORNIA	38.1727	-108.5785	6198.5	II
05-085-06008	OTHO AYERS 1-0-30	UNION OIL COMPANY OF CALIFORNIA	38.2955	-108.8954	5029.5	I
05-085-06009	MOON MESA UNIT (FED) 1	MOBIL OIL CORPORATION	38.4627	-108.7004	6535	II
05-085-06011	FEDERAL SINBAD RIDGE UNIT 14-14	GRYNBERG* JACK DBA GRYNBERG PETROLEUM CO	38.4105	-108.9403	7258	I
05-085-06012	WILD STEER UNIT-FEDERAL 32-24	GRYNBERG* JACK DBA GRYNBERG PETROLEUM CO	38.2278	-108.8041	6363	I
05-085-06013	FEDERAL MARTIN MESA 33-3	GRYNBERG* JACK DBA GRYNBERG PETROLEUM CO	38.3548	-108.8397	4974.4	I

API	WELL_NAME	OPERATOR	LAT	LONG	ELEV (FT)	PHASE
05-085-06014	FEDERAL WILD STEER UNIT 32-15	GRYNBERG* JACK DBA GRYNBERG PETROLEUM CO	38.3300	-108.9508	6217	I
05-085-06018	FEDERAL 34-21	GRYNBERG* JACK DBA GRYNBERG PETROLEUM CO	38.3085	-108.9692	6566	
05-085-06029	WRAY MESA 1	AMERICAN HUNTER EXPLORATION LTD	38.3046	-108.9610	6426.5	I
05-085-06033	HAUKELID 35-1	CNG PRODUCING CO	38.3835	-109.0485	7708	I
05-085-06034	UNOCAL-FEDERAL 1-P35	UNION OIL COMPANY OF CALIFORNIA	38.2785	-108.4834	6427	II
05-085-06036	BULL CANYON 14-14	BROWN INC* TOM	38.1591	-108.8182	7002	I
05-085-06037	SAWTOOTH 1-22	CABOT OIL & GAS CORPORATION	38.2295	-108.6252	6051	
05-085-06039	CIMARRON FEDERAL 25-31	ENCANA OIL & GAS (USA) INC	38.2989	-109.0352	7331	I
05-085-06040	SABERTOOTH 1-2	CABOT OIL & GAS CORPORATION	38.2690	-108.7047	6395	I
05-085-06043	BEDROCK UNIT 16-7-47-18	DEVON ENERGY PRODUCTION COMPANY LP	38.3376	-108.8921	5093	I
05-085-06044	WILD STEER 27-41	PATARA OIL & GAS LLC	38.2047	-108.7398	7051 (GL)	
05-085-06045	BEDROCK UNIT 6-4-47-19	CLEARY PETROLEUM CORPORATION	38.3586	-108.9728	5335	I
05-085-06046	SOUTH NUCLA UNIT 5-22	REDWINE RESOURCES INC	38.2726	-108.4370	6034	II
05-085-06047	SOUTH NUCLA UNIT 1-32	REDWINE RESOURCES INC	38.2695	-108.3601	6339	II
05-085-06049	WRAY MESA 36-34-47-20	CCI PARADOX UPSTREAM LLC	38.2873	-109.0211	7299	
05-113-05004	EGNAR 1	REYNOLDS MINING CORPORATION	37.9951	-108.9383	7198	II
05-113-05006	PURE-FEDERAL 1	BARRETT RESOURCES CORP	38.0221	-108.6226	6563.5	
05-113-05007	SOUTH GYPSUM VALLEY UNIT 1	THREE STATES OIL COMPANY	38.0275	-108.7280	6045	II
05-113-05008	BIG GYPSUM VALLEY UNIT 1	SHELL OIL COMPANY	38.0351	-108.6865	6169.7	II
05-113-05009	EGNAR UNIT 3	BELCO PETROLEUM CORPORATION	38.0357	-109.0031	6873	II
05-113-05011	EGNAR UNIT 2	BELCO PETROLEUM CORPORATION	38.0420	-108.9705	6917	II
05-113-05012	EGNAR UNIT #1	PATARA OIL & GAS LLC	38.0493	-108.9976	6886	II
05-113-05016	NORTH GYPSUM VALLEY UNIT 1	SHELL OIL CO	38.0949	-108.7608	6927	II
05-113-05017	MCINTYRE CANYON UNIT 1	PATARA OIL & GAS LLC	38.1007	-108.9889	6502	I
05-113-05018	HAMM CANYON 1	FULTON*R.H.	38.1108	-108.8180	6514.6	
05-113-05019	MCINTYRE CANYON 4	PURE OIL CO.	38.1117	-109.0101	6937	I
05-113-05020	BROAD UNIT 2	HUNT OIL COMPANY	38.1225	-108.5650	6980	II
05-113-05021	WEST GYPSUM VALLEY UNIT 1	SHELL OIL COMPANY	38.1228	-108.9322	6523.8	II
05-113-05022	MCINTYRE CANYON UNIT 5	PURE OIL CO.	38.1260	-109.0057	6831	I

API	WELL_NAME	OPERATOR	LAT	LONG	ELEV (FT)	PHASE
05-113-05023	BROAD UNIT 1	HUNT OIL COMPANY	38.1366	-108.5692	7183	II
05-113-05076	SOUTH GYPSUM VALLEY 2	SHELL OIL COMPANY	38.0786	-108.8686	6088.9	I
05-113-05077	MCINTYRE CANYON UNIT 3	UNION OIL COMPANY OF CALIFORNIA	38.0781	-108.9749	6633	I
05-113-05078	MCINTYRE CANYON UNIT 2	UNION OIL COMPANY OF CALIFORNIA	38.0928	-108.9930	6306	II
05-113-05080	ANDY'S MESA UNIT 1	CCI PARADOX UPSTREAM LLC	38.0283	-108.6191	6575	II
05-113-06001	ANDY'S MESA UNIT 2	UNION OIL COMPANY OF CALIFORNIA	38.0388	-108.6282	6504	
05-113-06002	ANDY'S MESA UNIT 3	BROWN INC* TOM	38.0459	-108.6381	6430	
05-113-06003	ANDY'S MESA-FEDERAL 4	CCI PARADOX UPSTREAM LLC	38.0539	-108.6596	6607	II
05-113-06004	ANDY'S MESA FEDERAL 5	UNION OIL COMPANY OF CALIFORNIA	38.0542	-108.6275	6484	II
05-113-06005	ANDY'S MESA-FEDERAL 6	CCI PARADOX UPSTREAM LLC	38.0543	-108.6460	6426	
05-113-06006	ANDY'S MESA UNIT 7	UNION OIL COMPANY OF CALIFORNIA	38.0242	-108.6053	6640	II
05-113-06007	ANDYS MESA UNIT 8	UNION OIL COMPANY OF CALIFORNIA	38.0602	-108.6698	6599	
05-113-06008	HAMM CANYON UNIT-GOV 1	ANADARKO PETROLEUM CORPORATION	38.1193	-108.8332	6523	I
05-113-06010	ANDYS MESA UNIT 9	UNION OIL COMPANY OF CALIFORNIA	38.0776	-108.7094	6590	
05-113-06011	MCINTYRE CANYON UNIT 6-H-18	CCI PARADOX UPSTREAM LLC	38.0790	-108.9988	6298	II
05-113-06012	USA C-11278 1-E-20	UNION OIL COMPANY OF CALIFORNIA	38.1396	-108.7764	6877	
05-113-06013	SLICKROCK 1	READ & STEVENS INC	38.0012	-108.7602	5690	II
05-113-06014	ANDERSON GOVERNMENT #1	READ & STEVENS INC	37.9769	-108.7789	5964	
05-113-06015	SUCKLA 1	READ & STEVENS INC	38.0053	-108.7782	5662	II
05-113-06018	SPUD PATCH UNIT 1	READ & STEVENS INC	38.0206	-108.8200	5581	I
05-113-06023	ANDY'S MESA UNIT 10-E28	CCI PARADOX UPSTREAM LLC	38.0472	-108.6459	6518	
05-113-06025	NICHOLAS WASH UNIT-FEDERA 1	HAMILTON OIL & GAS CORPORATION	38.0584	-108.8550	5844	I
05-113-06027	ANDYS MESA UNIT 11-E34	CCI PARADOX UPSTREAM LLC	38.0306	-108.6268	6554	
05-113-06030	CAPE HORN FEDERAL 1-28	COQUINA OIL CORPORATION	38.0515	-108.8658	5851	
05-113-06032	UNION FEDERAL 1-18	CHAMPLIN PETROLEUM COMPANY			6827	
05-113-06033	HAMM CANYON-FEDERAL 14-26 1	MERRION OIL & GAS CORP	38.1202	-108.8331	6508	I
05-113-06037	LONGRIDGE FEDERAL C-1	CHAMPLIN PETROLEUM COMPANY	38.0937	-108.7697	6926.6	
05-113-06041	FEDERAL 21-2	BROWN INC* TOM	38.0674	-108.8586	6000	I
05-113-06044	NICHOLAS WASH 22-1	APACHE CORPORATION	38.0643	-108.8504	5941	I
05-113-06046	STATE 1-16BD	COORS ENERGY COMPANY	38.1515	-108.5343	6389	II

API	WELL_NAME	OPERATOR	LAT	LONG	ELEV (FT)	PHASE
05-113-06062	FEDERAL 44-24	AMERICAN HUNTER EXPLORATION LTD	38.0556	-108.8017	5841.6	I
05-113-06065	ANDY'S MESA 12	CCI PARADOX UPSTREAM LLC	38.0320	-108.6117	6553	
05-113-06069	FOSSIL FEDERAL 5	CCI PARADOX UPSTREAM LLC	38.0634	-108.6822	6678	
05-113-06070	ANDYS MESA FEDERAL 13	CCI PARADOX UPSTREAM LLC	38.0554	-108.6507	6431	II
05-113-06071	ANDY'S MESA FEDERAL 16	CCI PARADOX UPSTREAM LLC	38.0419	-108.6326	6482	II
05-113-06072	ANDY'S MESA FEDERAL 15	CCI PARADOX UPSTREAM LLC	38.0364	-108.6249	6492	
05-113-06073	FOSSIL FEDERAL 2-19	CCI PARADOX UPSTREAM LLC	38.0658	-108.6716	6475	
05-113-06074	FOSSIL FEDERAL 8	CCI PARADOX UPSTREAM LLC	38.0741	-108.6956	6592	II
05-113-06076	FOSSIL FEDERAL 9	CABOT OIL & GAS CORPORATION	38.0786	-108.7048	6593	
05-113-06077	ANDYS MESA FEDERAL 14	CCI PARADOX UPSTREAM LLC	38.0584	-108.6442	6409	II
05-113-06079	ANDY'S MESA FEDERAL 17	CCI PARADOX UPSTREAM LLC	38.0494	-108.6479	6503	II
05-113-06080	MCINTYRE CANYON #17-21	CCI PARADOX UPSTREAM LLC	38.0772	-108.9913	6341	
05-113-06081	ANDY'S MESA FEDERAL 23	CCI PARADOX UPSTREAM LLC	38.0235	-108.6181	6610	
05-113-06082	NICHOLAS WASH 15-42	PATARA OIL & GAS LLC	38.0714	-108.8470	6203	I
05-113-06083	FOSSIL FEDERAL 1-19	CCI PARADOX UPSTREAM LLC	38.0660	-108.6719	6472	II
05-113-06084	ANDY'S MESA FEDERAL 20	CCI PARADOX UPSTREAM LLC	38.0420	-108.6434	6579	
05-113-06085	ANDY'S MESA FEDERAL 19	CCI PARADOX UPSTREAM LLC	38.0495	-108.6518	6570	II
05-113-06087	ANDY'S MESA FEE 21	CCI PARADOX UPSTREAM LLC	38.0567	-108.6572	6459	
05-113-06088	FOSSIL FEDERAL 2-20	CCI PARADOX UPSTREAM LLC	38.0609	-108.6574	6440	
05-113-06091	FOSSIL FEDERAL 1-13	CCI PARADOX UPSTREAM LLC	38.0764	-108.6890	6476	II
05-113-06092	FOSSIL FEDERAL 3-13	CCI PARADOX UPSTREAM LLC	38.0761	-108.6981	6573	
05-113-06096	FOSSIL FEDERAL 1-18	CCI PARADOX UPSTREAM LLC	38.0705	-108.6746	6450	
05-113-06097	ANDY'S MESA FEDERAL 25	CCI PARADOX UPSTREAM LLC	38.0410	-108.6397	6541	
05-113-06098	ANDY'S MESA FEDERAL 26	CCI PARADOX UPSTREAM LLC	38.0384	-108.6338	6494	
05-113-06099	FOSSIL FEDERAL 2-18	CCI PARADOX UPSTREAM LLC	38.0670	-108.6693	6440	
05-113-06100	ANDY'S MESA FEDERAL 24	CCI PARADOX UPSTREAM LLC	38.0476	-108.6508	6493	
05-113-06102	ANDY'S MESA FEDERAL 27	CCI PARADOX UPSTREAM LLC	38.0462	-108.6417	6438	II
05-113-06103	ANDY'S MESA FEDERAL 28	CCI PARADOX UPSTREAM LLC	38.0542	-108.6481	6421	
05-113-06106	MCINTYRE CANYON 8-34	BROWN INC* TOM	38.0956	-108.9789	6205	I
05-113-06107	ANDY'S MESA 18	PATARA OIL & GAS LLC	38.0503	-108.6221	6579	
05-113-06108	FOSSIL FEDERAL 4-20	CCI PARADOX UPSTREAM LLC	38.0631	-108.6665	6472	
05-113-06109	FOSSIL FEDERAL 1-20	CCI PARADOX UPSTREAM LLC	38.0630	-108.6590	6418	
05-113-06110	MAVERICK DRAW FEDERAL 20-42	CCI PARADOX UPSTREAM LLC	38.1345	-108.5501	6791	II
05-113-06111	ANDY'S MESA FEDERAL 34	CCI PARADOX UPSTREAM LLC	38.0255	-108.6173	6598	II
05-113-06112	ANDY'S MESA FEDERAL 32	CCI PARADOX UPSTREAM LLC	38.0507	-108.6539	6588	
05-113-06114	ANDY'S MESA FEDERAL 31	PATARA OIL & GAS LLC	38.0530	-108.6516	6493	
05-113-06115	ANDY'S MESA FEDERAL 30	CCI PARADOX UPSTREAM LLC	38.0549	-108.6567	6486	
05-113-06117	ANDY'S MESA FEDERAL 33	CCI PARADOX UPSTREAM LLC	38.0384	-108.6339	6493	

API	WELL_NAME	OPERATOR	LAT	LONG	ELEV (FT)	PHASE
05-113-06120	FOSSIL FEDERAL 5-19	CCI PARADOX UPSTREAM LLC	38.0636	-108.6825	6676	
05-113-06121	HARD LEFT 2-7	CABOT OIL & GAS CORPORATION	38.0964	-108.7832	7153	I
05-113-06122	ANDY'S MESA FEDERAL 29	CCI PARADOX UPSTREAM LLC	38.0579	-108.6591	6484	II
05-113-06124	ANDY'S MESA FEDERAL 36	CCI PARADOX UPSTREAM LLC	38.0297	-108.6227	6543	
05-113-06125	ANDY'S MESA FEDERAL 42	PATARA OIL & GAS LLC	38.0323	-108.6186	6560	
05-113-06126	ANDY'S MESA FEDERAL 37	CCI PARADOX UPSTREAM LLC	38.0478	-108.6338	6441	
05-113-06127	ANDY'S MESA FEDERAL 38	CCI PARADOX UPSTREAM LLC	38.0543	-108.6429	6418	
05-113-06128	ANDY'S MESA FEDERAL 40	CCI PARADOX UPSTREAM LLC	38.0445	-108.6444	6576	
05-113-06130	ANDY'S MESA FEDERAL 39	CCI PARADOX UPSTREAM LLC	38.0503	-108.6454	6451	
05-113-06131	ANDY'S MESA UNIT 41	CCI PARADOX UPSTREAM LLC	38.0583	-108.6442	6396	
05-113-06135	ANDY'S MESA UNIT 59	CCI PARADOX UPSTREAM LLC	38.0297	-108.6227	6651	
05-113-06136	ANDY'S MESA FEDERAL 53	CCI PARADOX UPSTREAM LLC	38.0429	-108.6246	6490	
05-113-06137	ANDY'S MESA 48	PATARA OIL & GAS LLC	38.0447	-108.6277	6480	
05-113-06138	ANDY'S MESA 47	CCI PARADOX UPSTREAM LLC	38.0448	-108.6276	6481	II
05-113-06139	ANDY'S MESA FEDERAL 58	CCI PARADOX UPSTREAM LLC	38.0255	-108.6173	6597	
05-113-06140	ANDY'S MESA FEDERAL54	CCI PARADOX UPSTREAM LLC	38.0332	-108.6286	6540	
05-113-06141	ANDY'S MESA FEDERAL 55	CCI PARADOX UPSTREAM LLC	38.0306	-108.6268	6558	
05-113-06142	ANDY'S MESA FEDERAL 60	CCI PARADOX UPSTREAM LLC	38.0323	-108.6186	6560	
05-113-06143	FOSSIL FEDERAL 1-24	CCI PARADOX UPSTREAM LLC	38.0666	-108.6840	6624	II
05-113-06144	FOSSIL FEDERAL	CCI PARADOX UPSTREAM LLC	38.0623	-108.6592	6422	II
05-113-06145	FOSSIS FEDERAL 4-13	CCI PARADOX UPSTREAM LLC	38.0736	-108.6968	6599	
05-113-06148	ANDY'S MESA UNIT 63	CCI PARADOX UPSTREAM LLC	38.0205	-108.6047	6661	II
05-113-06149	ANDY'S MESA 61	CCI PARADOX UPSTREAM LLC	38.0241	-108.6113	6609	II
05-113-06150	ANDY'S MESA 62	CCI PARADOX UPSTREAM LLC	38.0240	-108.6113	6609	
05-113-06151	FOSSIL FEDERAL 6-19	CCI PARADOX UPSTREAM LLC	38.0639	-108.6674	6452	
05-113-06159	SINGLE EAGLE 1	CCI PARADOX UPSTREAM LLC	38.0859	-108.7261	6651	II
05-113-06181	FOSSIL FEDERAL 9R	CCI PARADOX UPSTREAM LLC	38.0788	-108.7048	6597	
05-113-06199	FOSSIL FEDERAL 6-18	HUNTINGTON ENERGY LLC	38.0786	-108.6830	6402	
05-113-06210	MD FED	CCI PARADOX UPSTREAM LLC	38.1207	-108.5340	6886	
05-113-06220	SLICK ROCK FED 8-23-43-17	CRESCENT POINT ENERGY U.S. CORP	38.0062	-108.7642	5724	II
05-113-06225	ANDY'S MESA FED 64	CCI PARADOX UPSTREAM LLC	38.0422	-108.6442	6609.7	
05-113-06237	ANDY'S MESA FED 68	CCI PARADOX UPSTREAM LLC	38.0468	-108.6465	6518	
05-113-06238	ANDY'S MESA FED 65	CCI PARADOX UPSTREAM LLC	38.0468	-108.6464	6536	
05-113-06239	ANDY'S MESA FED 67	CCI PARADOX UPSTREAM LLC	38.0504	-108.6534	6594	
05-113-06240	ANDY'S MESA FEDERAL 66	CCI PARADOX UPSTREAM LLC	38.0504	-108.6534	6597	
05-113-06241	ANDY'S MESA FED 69	CCI PARADOX UPSTREAM LLC	38.0452	-108.6442	6533	
05-113-06244	SOUTH GYPSUM 31-30	CCI PARADOX UPSTREAM LLC	38.0428	-108.7944	5765	I
05-113-06250	ANDY'S MESA FED.	CCI PARADOX UPSTREAM LLC	38.0407	-108.6403	6563	
05-113-06251	ANDY'S MESA FEDERAL 76	CCI PARADOX UPSTREAM LLC	38.0556	-108.6513	6437	

API	WELL_NAME	OPERATOR	LAT	LONG	ELEV (FT)	PHASE
05-113-06252	ANDY'S MESA FED. #70	CCI PARADOX UPSTREAM LLC	38.0531	-108.6517	6459.6	
05-113-06253	ANDY'S MESA FED. #71	CCI PARADOX UPSTREAM LLC	38.0501	-108.6482	6509.6	
05-113-06254	ANDY'S MESA FED 75	CCI PARADOX UPSTREAM LLC	38.0391	-108.6333	7062	
05-113-06255	ANDY'S MESA FEDERAL #72	CCI PARADOX UPSTREAM LLC	38.0501	-108.6482	6510	
05-113-06257	ABBEY 34-16A	CABOT OIL & GAS CORPORATION	38.1492	-108.9711	7042	I
05-113-06806	ANDY'S MESA FEE 22	CCI PARADOX UPSTREAM LLC	38.0485	-108.6421	6420	
43-037-11191	HORSETHIEF CANYON UNIT 1-5	SUPERIOR OIL COMPANY	38.3058	-109.0744	7323	I
43-037-11353	ISLAND MESA UNIT 1	UNION OIL CO OF CALIFORNIA	38.1616	-109.0621	6464	I
43-037-30018	HORN UNIT FED 1	CHAMBERS & KENNEDY	38.2862	-109.0723	7320	I
43-037-30594	HORN UNIT 17-1	DAVIS OIL COMPANY	38.2801	-109.0783	7247	I
43-037-30923	TXC/HUBER FEDERAL 1-15	TRANSCO EXPLORATION CO	38.3631	-109.1545	7618.8	II

Appendix B: Images of well logs from all area wells

Appendix B is not publicly available because it contains proprietary data licensed from private sources.

Appendix C: Images of porosity logs from selected wells

Appendix C is not publicly available because it contains proprietary data licensed from private sources.