BUREAU OF RECLAMATION

Technical Memorandum 86-68330-2023-1

2022 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

Colorado River Basin Salinity Control Program
Upper Colorado Region

U.S. Department of the Interior May 2023

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

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.

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Prepared by:

Bureau of Reclamation
Technical Service Center
Denver, Colorado

U.S. Department of the Interior **May 2023**

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LISA BLOCK Digitally signed by LISA BLOCK
Date: 2023.05.08 08:35:04 -06'00'

Lisa Block
Geophysicist, Geomorphology and Seismology Group, 86-68330

GLENDA BESANA-OSTMAN Digitally signed by GLENDA BESANA-OSTMAN
Date: 2023.05.08 09:10:48 -06'00'

Glenda Besana-Ostman
Geologist, Geomorphology and Seismology Group, 86-68330

CHRISTOPHER WOOD
2023.05.10 15:44:31 -06'00'

Christopher Wood
Geophysicist, Geomorphology and Seismology Group, 86-68330

JUSTIN SCHWARZER Digitally signed by JUSTIN SCHWARZER
Date: 2023.05.11 07:53:28 -06'00'

Justin Schwarzer
Geophysicist, Geomorphology and Seismology Group, 86-68330

JONG BEOM KANG Digitally signed by JONG BEOM KANG
Date: 2023.05.10 15:55:35 -06'00'

Jong Boem Kang
Civil Engineer, Geotechnical Laboratory and Field Support Group, 86-68550

DAVID HEESZEL
2023.05.11 07:51:08 -06'00'

David Heeszel
Geophysicist, Geomorphology and Seismology Group, 86-68330

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Peer Review Certification

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

JUSTIN BALL Digitally signed by JUSTIN BALL
Date: 2023.05.09 09:31:12 -06'00'

Justin Ball
Geophysicist, Geomorphology and Seismology Group, 86-68330

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Acronyms and Abbreviations

dB	decibel
EPA	Environmental Protection Agency
ft	feet
g	standard acceleration of gravity, equivalent to 9.80665 m/s^2
gpm	gallons per minute
km	kilometers
l/min	liters per minute
MASIP	Maximum Allowable Surface Injection Pressure
M_D	duration magnitude
Mgal	millions of gallons
M_L	local magnitude
MPa	MegaPascal
MSL	Mean Sea Level
M_W	Moment magnitude
NW	Northwest
psi	pounds per square inch
PVB	Paradox Valley Brine
PVSN	Paradox Valley Seismic Network
PVU	Paradox Valley Unit
SE	Southeast
UIC	Underground Injection Code
USGS	United States Geological Survey

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Paradox Valley Seismic Network

I. Introduction

The Paradox Valley Seismic Network (PVSN) monitors earthquakes induced by injection operations at the Bureau of Reclamation's (Reclamation) Paradox Valley Unit (PVU) deep disposal well, as well as local naturally occurring earthquakes. This report summarizes PVSN operations and the data recorded during calendar year 2022. We provide project background information in Section II, including the history of PVU injection operations and details of the seismic network. In Section III, we present PVSN network operations during 2022, including maintenance of the seismic stations and data acquisition systems and annual network performance. The earthquake data recorded during the year are discussed in Section IV and compared to historical seismicity trends.

II. Project Background

A. Paradox Valley Unit

Reclamation's PVU, a component of the Colorado River Basin Salinity Control Program, intercepts salt brine that would otherwise flow into the Dolores River, a tributary of the Colorado River. PVU is in western Montrose County, approximately 90 km southwest of Grand Junction, Colorado and 16 km east of the Colorado-Utah border (Figure II-1). The Dolores River flows from southwest to northeast across Paradox Valley (Figure II-2), which was formed by the collapse of a salt-cored anticline (Figure II-3). Due to the presence of the salt diapir underlying Paradox Valley, groundwater within the valley is nearly eight times more saline than ocean water. To prevent this highly saline groundwater from entering the Dolores River and degrading water quality downstream, the brine is extracted from nine shallow wells within the valley near the Dolores River. The diverted brine is injected at high pressure into a deep disposal well, designated as PVU Salinity Control Well No. 1. The disposal well is located approximately 1.5 km southwest of Paradox Valley, near the town of Bedrock (Figure II-2).

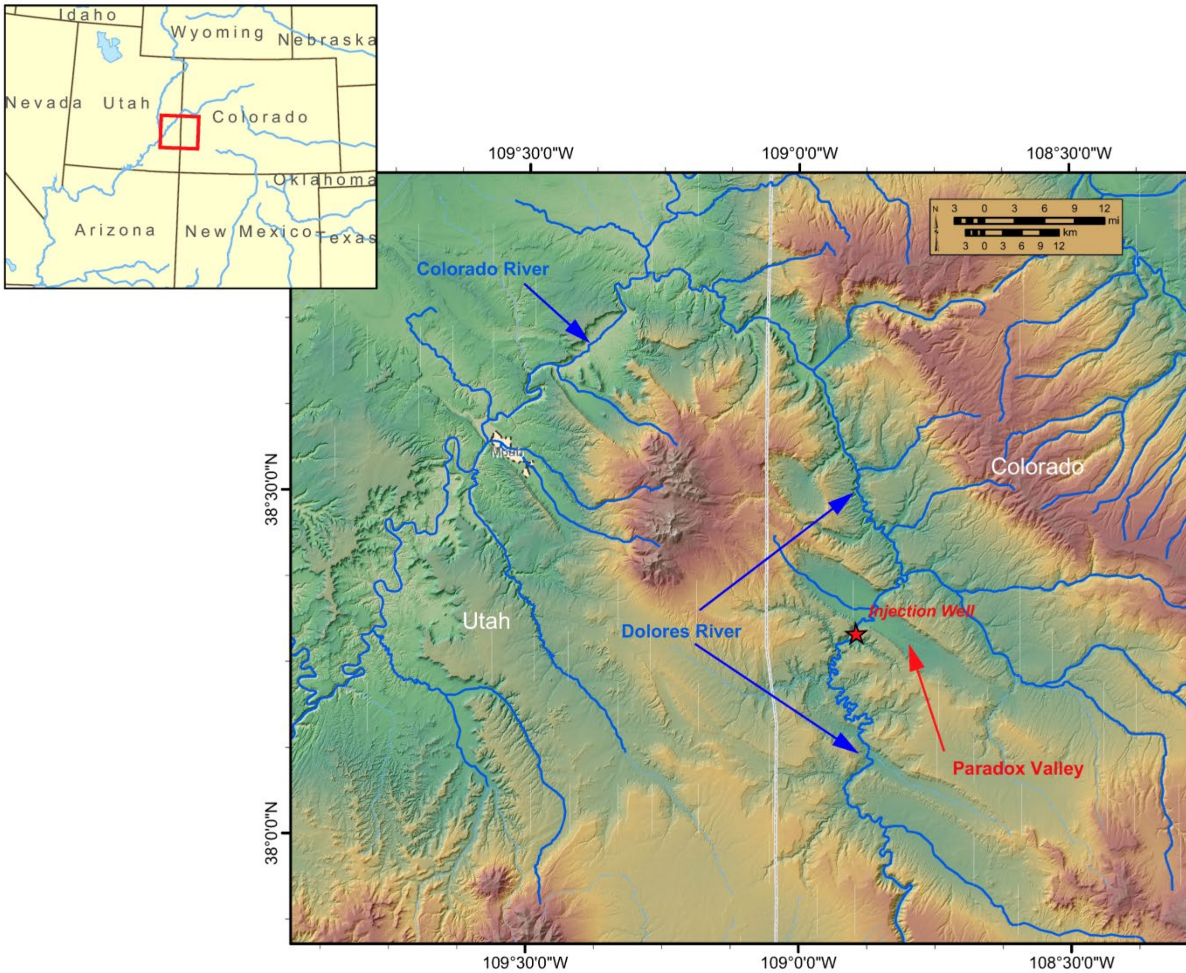


Figure II-1: Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado (red star).

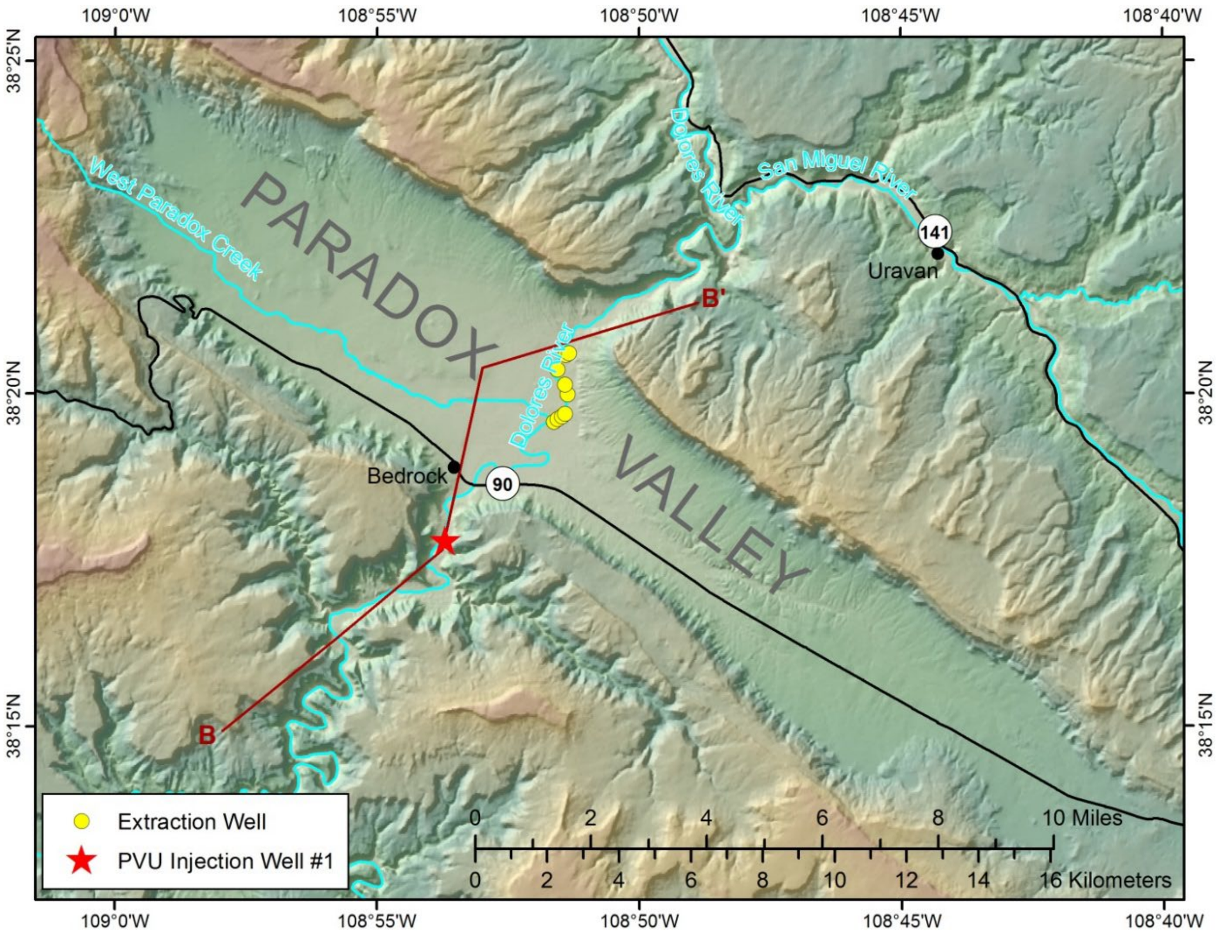


Figure II-2: Location of the Paradox Valley Unit extraction wells (yellow circles) and injection well (red star). Cross section B-B´ is shown in Figure II-3.

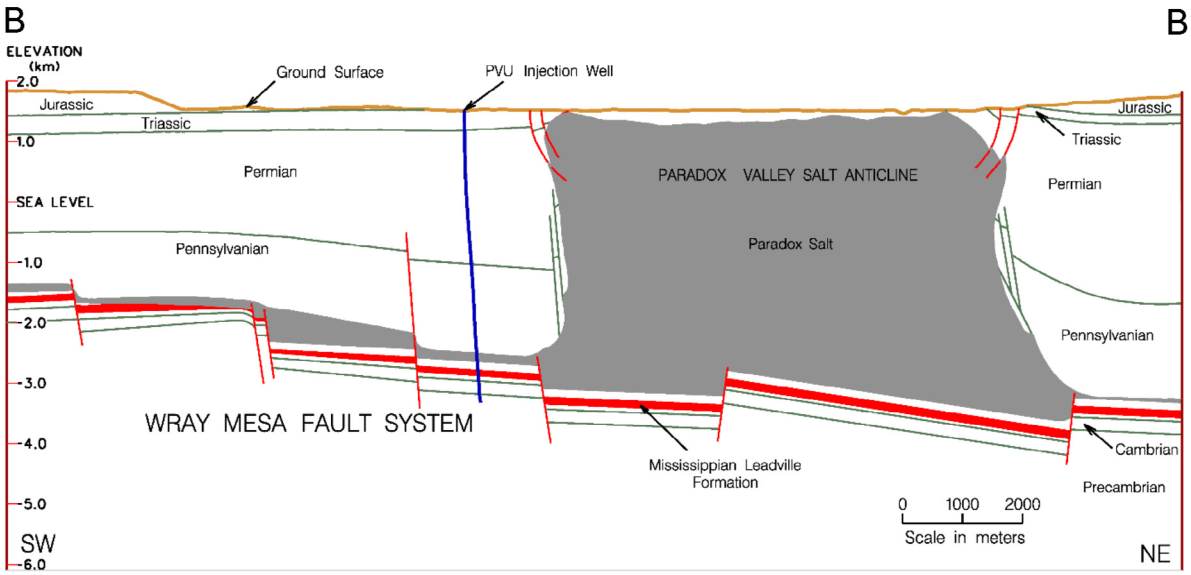


Figure II-3: Vertical cross section roughly perpendicular to Paradox Valley, looking to the northwest. The location of the cross section is shown in Figure II-2. Based on figure from Bremkamp and Harr (1988).

PVU Salinity Control Well No. 1 was completed in 1987 to a total depth of 4.88 km (approximately 16,000 ft). The well was built to Environmental Protection Agency (EPA) Underground Injection Code (UIC) Class I standards ("Isolate hazardous, industrial and municipal wastes through deep injection") but was permitted in 1995 by EPA as a Class V disposal well ("Manage the shallow injection of non-hazardous fluids"). The well penetrates Triassic- through Cambrian-age sedimentary rock layers and granitic Precambrian basement (Figure II-3). Based on regional core and log data interpretation, the Mississippian Leadville carbonate was selected as the primary injection zone with the upper Precambrian as a secondary zone (Bremkamp and Harr, 1988). The overlying Paradox salt formation acts as a confining layer. The well casing of PVU Well No. 1 (constructed of Hastelloy C- 276, a nickel-molybdenum-chromium alloy) was perforated at a spacing of ~20 perforations per meter in three major intervals between 4.3 km and 4.8 km depth. Plan and vertical views of the wellbore, with near-wellbore stratigraphy and the perforation intervals, are shown in Figure II-4.

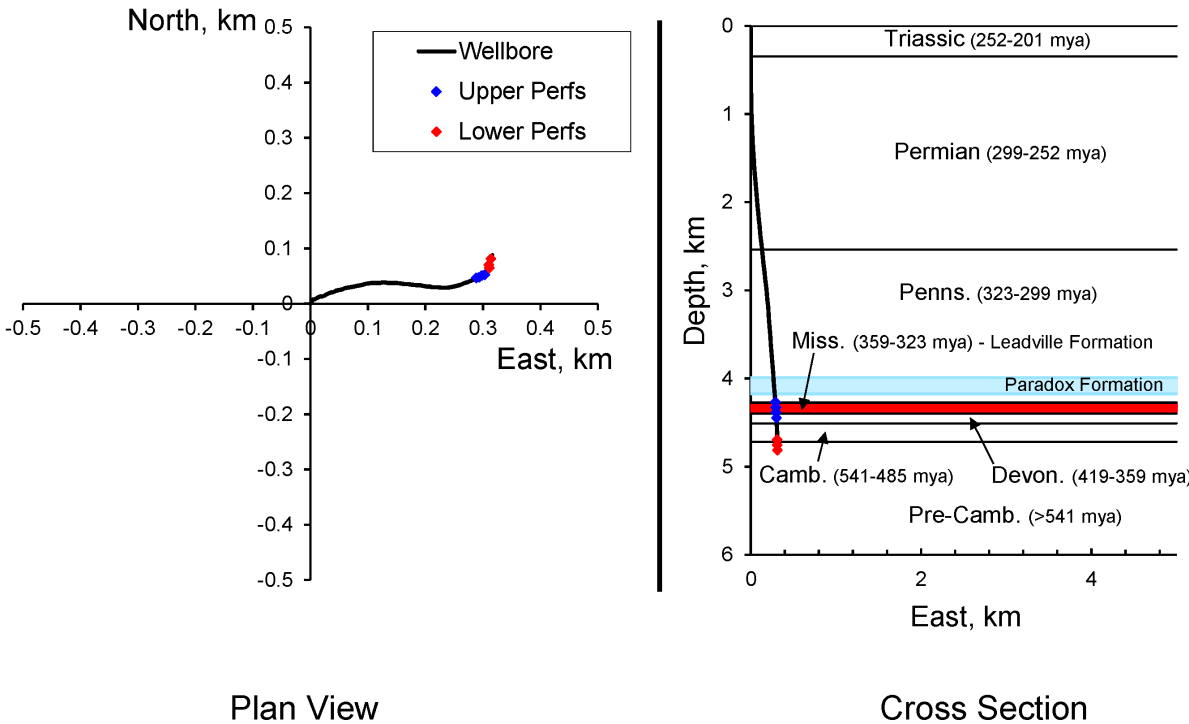


Figure II-4: PVU injection well in plan view (left) and north-viewing vertical cross section (right). Figure includes the near-wellbore stratigraphy and locations of the upper and lower casing perforations. The primary target injection formation, the Leadville, is shown in red, and the Paradox formation confining layer is shown in blue. The ages of the geologic time periods are taken from the Geological Society of America Geologic Time Scale version 4.0 (Walker et al., 2013). The ages shown represent the entire span of any given geologic time period and do not necessarily represent the precise ages of the rocks present at the PVU injection well.

B. PVU Injection Operations

Between 1991 and 1995, Reclamation conducted a series of seven injection tests, an acid stimulation test, and a reservoir integrity test at PVU. These tests were conducted to qualify for a Class V permit for deep disposal from the EPA. Near-continuous, long-term brine disposal began in July 1996, after the EPA granted the permit. During long-term injection, Reclamation instituted six major changes in operations. Five of these changes were implemented to mitigate the potential for unacceptable seismicity, and one change was made to improve injection economics. The seven time periods defined by these operational changes are considered separate injection phases, as described below. Plots of the daily average injection flow rates, daily average surface injection pressures, daily average downhole pressures (at a depth of 4.3 km), and cumulative injected fluid volumes during PVU injection operations are shown in Figure II-5. The downhole pressures shown were computed from measured surface pressures using the density of the brine column in the wellbore.

1. Phase I - July 22, 1996 to July 7, 1999

During this initial phase of near-continuous injection, brine was injected at a nominal flow rate of 345 gpm (~1306 l/min), resulting in an average surface pressure of about 4,950 psi (~34.1 MPa). This corresponded to approximately 11,800 psi (~81.4 MPa) downhole pressure at 4.3 km depth. To maintain this flow rate, three constant-rate pumps were used, each operating at 115 gpm. The surface pressure occasionally approached the wellhead pressure safety limit of 5,000 psi. This safety limit was based on the operational specifications of the injection and wellhead equipment. It also corresponded to the maximum allowable surface injection pressure (MASIP) defined in the injection permit issued by EPA, which is intended to prevent a breach of the geologic confining layer (the Paradox salt). When the surface pressure approached the MASIP, the injection rate was reduced by shutting down one or two of the injection pumps, allowing the pressure to drop a few hundred psi before returning to a three-pump operation. These partial shutdowns occurred frequently and had typical durations of a few minutes to a few days. This operational protocol resulted in relatively constant surface and downhole pressures (Figure II-5). Periodic maintenance shutdowns of all pumps also occurred and lasted for one to two weeks. In mid-1997, a 71-day total shutdown was needed to replace the operations and maintenance contractors. The *Phase I* protocols resulted in an overall average injection rate of roughly 300 gpm (1136 l/min), and the total volume of fluid injected was 427 Mgal (1.6 x 10^9 liters).

The injectate during *Phase I* was a mixture of 70% Paradox Valley Brine (PVB) and 30% freshwater from the Dolores River. A geochemical study had predicted that if 100% PVB were injected, it would interact with connate fluids and the dolomitized Leadville Limestone at the initial formation temperatures and pressures, resulting in the precipitation of calcium sulfate. This precipitation would lead to reduced permeability (Kharaka et al., 1997).

2. Phase II - July 8, 1999 to May 27, 2000

Following a local magnitude M_L 3.6 earthquake in June 1999 and an M_L 3.5 earthquake in July 1999, PVU altered the injection schedule to include a 20-day total shutdown (shut-in) every six months. Prior to these events, it was noted that the rate of seismicity in the near-wellbore region (i.e., within about a 2-km radius around the wellbore) decreased during and following unscheduled maintenance shutdowns. Similar decreases in seismicity also were observed during the shutdowns following the injection tests of 1991 through 1995. It was therefore hypothesized that the biannual shutdowns might reduce the potential for inducing large-magnitude earthquakes by allowing extra time for the injectate to diffuse from the pressurized fractures and faults into the formation rock matrix. When injecting during this phase, the average flow rate was the same as during Phase I. One hundred and eighteen Mgal (4.5 x 10^8 liters) of fluid were injected during Phase II.

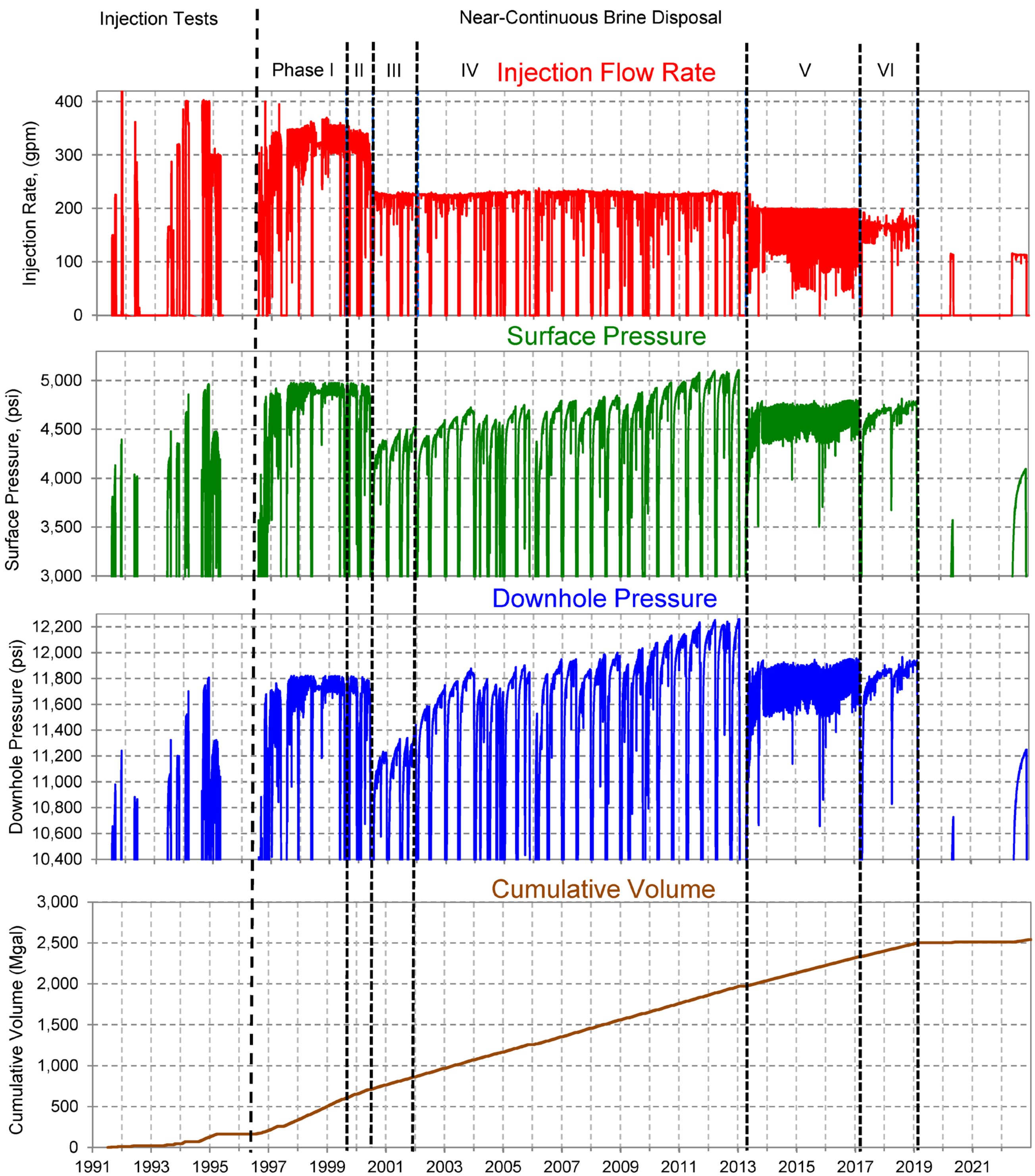


Figure II-5: Daily average injection flow rate, daily average surface injection pressure, daily average downhole pressure at 4.3 km depth, and cumulative volume of brine injected during PVU injection operations. The downhole pressures are computed from the measured surface pressures using the density of the brine column in the well. The vertical dashed lines delineate the injection phases discussed in the text.

3. Phase III - June 23, 2000 to January 6, 2002

Immediately following an M_L 4.3 earthquake on May 27, 2000, injection ceased for 28 days. During this shutdown period, Reclamation evaluated the existing injection protocol and its effect on induced seismicity. The decision was made to reduce the injection flow rate, expecting that this change would likely reduce the potential for inducing large-magnitude earthquakes. On June 23, 2000, PVU injection resumed using two pumps rather than alternating between two and three pumps. The biannual 20-day shutdowns were maintained. The nominal flow rate during *Phase III,* while injecting using two pumps, was 230 gpm (~871 l/min). Accounting for the two 20-day shut-ins per year, the average injection flow rate was approximately 205 gpm (776 l/min), a decrease of about 32% compared to *Phase I*. During this phase, 156 Mgal (5.9×10^8 liters) of fluid were injected.

4. Phase IV - January 7, 2002 to January 24, 2013

During October 2001, the need to dilute PVB with fresh water prior to injection was re-evaluated. Lab testing of drill cores conducted in 1993 detected no evidence of precipitation or plugging for either a 70 % brine / 30 % freshwater mixture or for a 100 % brine mixture, at temperatures of 270 °F or 300 °F (Envirocorp Services and Technology Inc., 1993). In addition, temperature logging was performed multiple times between 1992 and June 2001 and recorded substantial near-wellbore cooling at the depth of the Leadville Formation (~70° to ~130° F decrease) (Subsurface Technology, 2001). The temperature measurements recorded in the upper Leadville in 2001 indicated "a super-cooled buffer zone, some distance from the well, which will prevent the creation of conditions favorable to calcium sulfate precipitation" (Subsurface Technology, 2001, pg. 18). Hence, if precipitation were to occur, it would not be near the wellbore perforations where clogging might be a concern (Nicholas, 2001). In addition, the high PVU injection pressures would likely act to keep fractures open within the target injection formations, even if some precipitation were to occur (McKinley, 2001). Further analyses indicated that, if precipitation occurs, its maximum expected rate is ~8 tons of calcium sulfate per day (Mahrer et al., 2003). To put this amount into perspective, injecting at ~230 gpm and assuming a brine density of 9.86 lbs/gal (17% denser than freshwater) results in a daily injection mass of ~1633 tons. The maximum expected precipitate, therefore, is only ~0.5% of the daily injection mass.

After considering this new information, the decision was made to begin injecting 100% PVB to partially offset the reduction in salt disposal rates resulting from the decreased injection rate implemented in *Phase III.* Injection of 100% PVB began on January 7, 2002, following the December-January 20-day shutdown, and has been maintained since. The injection rate implemented in *Phase III* (230 gpm) and biannual 20-day shutdowns were continued. The volume of fluid injected during *Phase IV* was 1,110 Mgal (4.2×10^9 liters).

Because of the decreased flow rate in *Phase III* and *Phase IV* compared to the earlier phases, the surface pressure remained below the MASIP of 5,000 psi for over a decade (mid-2000 to 2011). Hence, there was no need to frequently alter flow rates, as had been done during *Phases I* and *II*. Nevertheless, the continued injection during *Phases III* and *IV* resulted in a trend of increasing maximum surface and downhole pressures (Figure II-5). In addition, because of the increased density of the 100% PVB injected during *Phase IV* over the 70% PVB / 30% freshwater mix injected previously, the computed downhole pressures increased by ~300 psi immediately following the change to 100% brine in January 2002.

In response to the increasing surface injection pressures, Reclamation submitted a request to EPA in 2004 to increase the MASIP. EPA approved the request, pending infrastructure upgrades to increase the injection equipment pressure safety limit. In 2009, the PVU injection wellhead equipment was upgraded to a pressure safety limit of 10,000 psi. An increase in the MASIP to 5350 psi was formally incorporated into the injection permit reauthorization issued by EPA in August 2011.

5. Phase V - April 17, 2013 to March 12, 2017

An induced earthquake with M_L 4.4 (corresponding to moment magnitude M_W 4.0) occurred ~8 km northwest of the PVU injection well on January 24, 2013 (Block et al., 2014). In response to this earthquake, injection was halted while a reassessment of the seismic hazard associated with PVU injection was performed. Analyses of the seismic and injection data indicated that the potential for inducing large felt events would be reduced by decreasing the long-term average injection pressures (Block and Wood, 2009; Wood et al., 2016). Pressure-flow modeling indicated that reducing the flow rate would lead to a corresponding reduction in wellhead pressures. Forward modeling was used to evaluate the effect of different flow rates on wellhead pressures (Wood et al., 2016). In addition, the pressure-flow modeling indicated that changing the injection well shut-in schedule to one with shorter, more frequent shut-ins would result in a reduction in the average wellhead pressure, compared to the biannual 20-day shut-ins previously used.

As a result of these analyses, the decision was made in April 2013 to reduce the injection flow rate and increase the frequency of injection well shut-ins. Due to the lag time in obtaining pump plungers that would allow injection at a lower flow rate, injection was initially resumed on April 17, 2013, maintaining the flow rate at 230 gpm and implementing a 36-hour shut-in every week. On June 6, 2013, following the installation of the new plungers, the flow rate was reduced to 200 gpm, and the shut-in length was reduced to 18 hours, maintaining the frequency of one shut-in per week. A shut-in duration of 18 hours was chosen so that the total annual shut-in time would be approximately equivalent to that scheduled previously with the biannual 20-day shut-ins. Hence, the nominal flow rate during *Phase V* (200 gpm) was decreased by 13 % from that during *Phase IV* (230 gpm), and the total duration of planned shut-ins remained the same.

Because of the frequency of the new shut-in schedule, the durations of any unplanned shut-ins (such as those periodically required for equipment maintenance) were tracked, and those hours were subtracted from the weekly scheduled 18-hour shut-ins. The durations of unplanned shut-ins had not been tracked and subtracted from the biannual 20-day shut-ins during earlier injection phases, and hence the total shut-in time during previous years had sometimes varied substantially, depending on the number and duration of unplanned shut-ins required. Hence, while the nominal flow rate during *Phase V* was decreased by 13% from that during *Phase IV*, the effective decrease in flow rate was less than this value due to the difference in total shut-in time. The average flow rate during *Phase V* was 177 gpm, which is ~9.7 % less than the average flow rate of 196 gpm during the preceding three years (2010-2012). Three hundred and sixty-four Mgal (1.4 x 10^9 liters) of fluid were injected during this phase.

6. Phase VI - April 8, 2017 to March 4, 2019

Beginning on March 12, 2017, the injection well was shut in for 27 days. Injection was resumed on April 8 at a ~5 % reduced effective flow rate. These changes were made partially in response to the observation that the rates and magnitudes of PVU-induced earthquakes had been increasing for ~1.5 years. The occurrence of an M_D 2.9 earthquake nearly 13 km from the injection well (on 3/12/17) further influenced the decision to reduce the effective flow rates.

The reduced effective flow rate was initially achieved by changing the size of the plungers from 2.000" to 1.875", which reduced the nominal flow rate from 200 gal/min to 174 gal/min. At the same time, the duration of the weekly shut-ins was reduced from 18 hours to 6 hours. Two pumps were run continuously, except for the weekly plant shutdowns. Considering the weekly shut-ins, the effective average flow rate was 168 gal/min.

In September 2017, premature wear of the new 1.875" plungers forced the reinstallation of larger plungers in two of the three pumps (one 2.125" plunger and one 2.000" plunger). As a result, injection operations were changed to accommodate the larger plungers (and corresponding rate increase) by eliminating the six-hour weekly plant shutdown and starting daily pump shutdowns on the pumps with larger plungers. The weekly shutdown of the single pump with the 1.875" plunger continued. Injection was then continuous, with either one or two pumps running at any given time. The target daily injection volume was 242,000 gallons, corresponding to a target average injection rate of 168 gpm. Hence, the effective average flow rate remained the same as with the smaller plungers. The total volume of fluid injected during *Phase VI* was 167 Mgal (6.3 x 10^8 liters).

An induced earthquake with moment magnitude M_W 4.5 occurred ~1.6 km southwest of the PVU injection well on March 4, 2019 (Block et al., 2020). This earthquake was the largest PVU-induced earthquake to date and was substantially larger than the M_W 4.0 earthquake of January 2013. More than 2,000 aftershocks occurred in the first five months following the main shock, resulting in the highest near-well seismicity rates in 20 years. Analyses indicate that aftershocks will continue to occur for several years at gradually decreasing rates (Block et al., 2020). The PVU injection well had been shut down for a few hours at the time of the M_W 4.5 earthquake to accommodate equipment maintenance activities. The well remained shut down for more than a year while detailed analyses of the M_W 4.5 earthquake and its numerous aftershocks were conducted. This extended shutdown also allowed formation pressures and aftershock rates to decay substantially.

7. Post- March 2019 Operations

Injection resumed on April 21, 2020 for a planned six-month test period. The purpose of the test was to evaluate how the well would perform after being shut in for more than a year. Specifically, the pressure response of the well was monitored to determine whether any potential near-wellbore precipitation in the injection formations during the extended shutdown has altered the injection pressure response. In addition, seismicity was closely monitored for any changes in induced seismicity response. Injection during this test was at a near-constant rate of 115 gpm, a 32% reduction compared to the flow rate during *Phase VI.*

The injection test was prematurely terminated on May 29, 2020, in response to a request by Reclamation management for an external peer review of injection operations. According to a transient analysis of the wellhead pressure data recorded immediately following the injection test and comparison to historical PVU pressure data, "parallel early-time slopes and equal durations of storage effects from 2017 to 2020 suggest that the extended 2019 shut-in did not significantly alter the early-time transient behavior of the well" (Petrotek, 2021). However, the injection test report also states, "It is clear that a comprehensive falloff analysis would require a significantly longer period of time and the application of downhole pressure gauges". No change in the induced seismicity attributable to the injection test was observed. Following this test, the well remained shut down for more than a year.

A second, longer injection test was initiated on June 2, 2022. The test was conducted for six months, at a continuous target flow rate of 115 gpm (effective flow rate was ~113 gpm). The test ended on the morning of December 2, 2022. Similar to the shorter test in 2020, this test was conducted to evaluate well and reservoir performance following the extended injection well shut-in, and induced seismicity was closely monitored. Analyses of the injection data indicate that the extended injection well shut-in "did not result in any apparent plugging or other impairment of the injection wellbore, communication through the tubing, or plugging of the perforations" (Petrotek, 2023). In addition, the data do not indicate "significant changes in the properties of the near wellbore region" (Petrotek, 2023). Analyses of the seismic data recorded during the test indicated "no anomalous changes in the rates or magnitudes of induced earthquakes" (Nicholas, 2023).

Following the six-month injection test, flow and geomechanical modeling was performed to evaluate the changes in pore pressures and stresses that had occurred during the test and to model trends for five different scenarios for future injection operations. The results indicate that pressures in areas close to the injection well (within ~4-6 km) would remain below their pre-2019 values for several years at all flow rates modeled, helping to keep the seismic hazard reduced in that area. Pressures at large distances from the well (> ~7-8 km) were predicted to continue increasing at any flow rate, and the pressure trends in some areas at intermediate distances from the well were found to be very sensitive to the selection of injection flow rate (Block and Kang, in preparation).

Based on the injection data analyses, observed induced seismicity, and flow/geomechanical modeling results, the decision was made to continue operating the injection well in test status, at a target flow rate of 115 gpm, until BOR management completes their assessment of future injection well operations. Injection was resumed at this rate on January 23, 2023.

C. Seismic Monitoring

1. Paradox Valley Seismic Network

During the planning for PVU, it was recognized that earthquakes could be induced by the high-pressure, deep-well injection of brine. This was based on a comparison to other deep-well injection projects in Colorado, including the Rocky Mountain Arsenal, near Denver, and oil and gas extraction projects near Rangley (Gibbs et al., 1973; Hsieh and Bredehoeft, 1981; Nicholson and Wesson, 1990; Raleigh et al., 1976).

In 1983, eight years before the first injection at PVU, Reclamation commissioned a seismic monitoring network to characterize the pre-injection, naturally occurring seismicity in the Paradox Valley region, and to monitor earthquakes that might be induced once injection operations began. The Paradox Valley Seismic Network (PVSN) was the product of these efforts. Field equipment for an initial 10-station network was acquired and installed in 1983 by the U.S. Geological Survey (USGS), under a Memorandum of Agreement with Reclamation. Nine of these original seismic stations were vertical-component, and the remaining station (PV08) was three-component. All stations used short-period seismometers (natural frequency of 1 Hz), and analog telemetry. Continuous data recording and archiving began in 1985. For the first several years of monitoring, seismic data from this network were acquired and processed by the USGS at their facilities in Golden, Colorado. In 1990, responsibility for data acquisition and analysis was assumed by Reclamation. The USGS continued to assist Reclamation with the maintenance of the field instrumentation and radio telemetry.

PVSN has been upgraded and expanded several times to modernize its instrumentation and improve the coverage of seismically active areas. In addition, some stations have been de-commissioned, either due to repeated vandalism or changing telemetry requirements. The locations of the original and current PVSN seismograph stations are shown in Figure II-6. Details about the stations are provided in Table II-1, including dates of operation, station type, and number of seismometer components. Table II-2 lists the station location names.

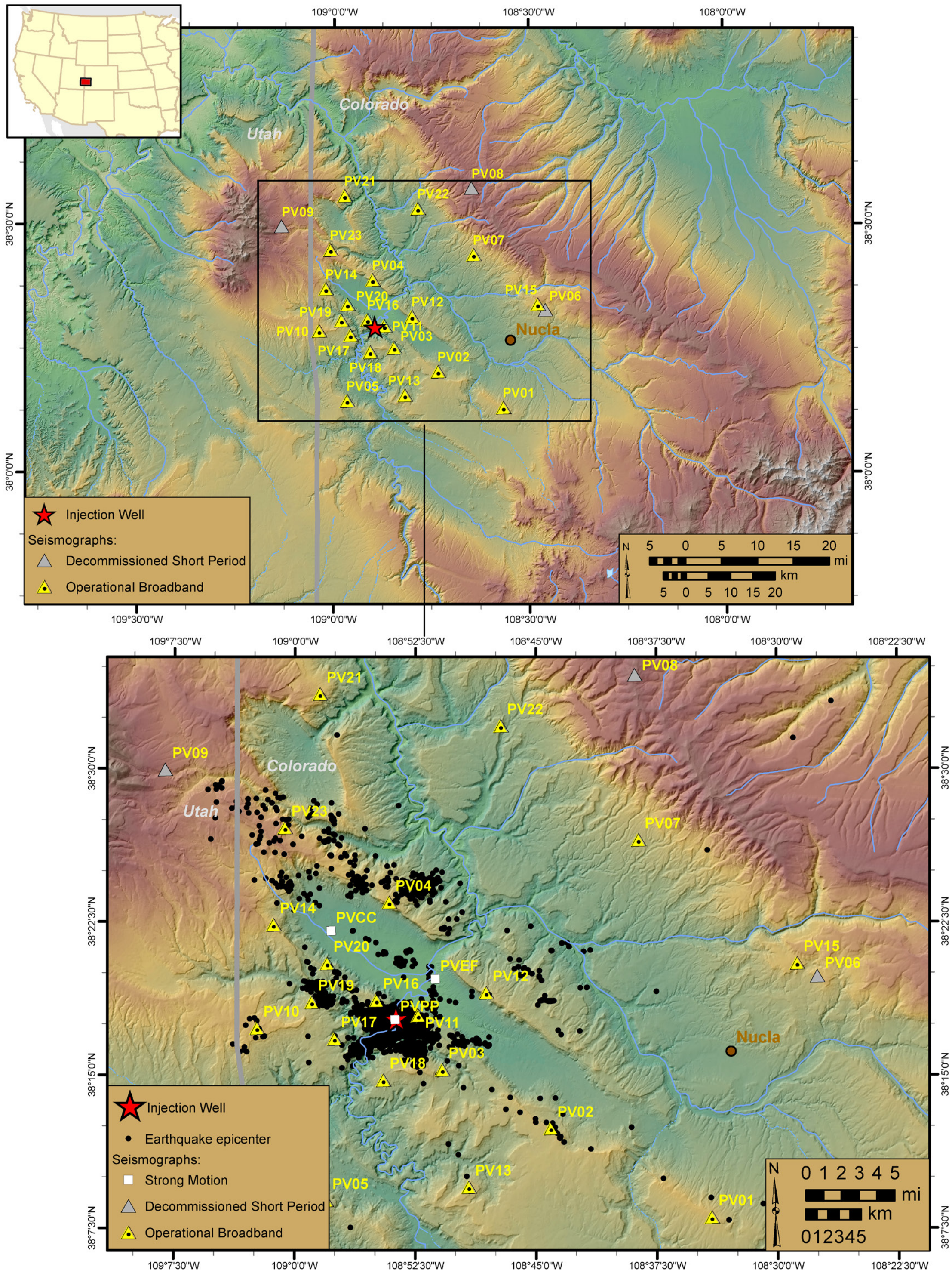


Figure II-6: Locations of the PVSN seismic stations, PVU injection well, and epicenters of earthquakes ≤ 10 km deep. PVCC, PVEF, & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Stations PV08 and PV09 were decommissioned when the network was upgraded to broadband digital instrumentation.

Table II-1: PVSN Station Locations and Characteristics

Station Name	Latitude deg., N	Longitude deg., W	Elev. m	Dates of Operation	Station Type	Sensor Direction
PV01	38.13	108.57	2191	5/83-7/16/15 5/10-present	short-period broadband	vertical triaxial
PV02	38.21	108.74	2177	5/83-8/27/11 10/08-present	short-period broadband	vertical triaxial
PV03	38.25	108.85	1972	5/83-7/16/15 10/08-present	short-period broadband	vertical triaxial
PV04	38.39	108.90	2176	5/83-6/06 5/07-present	short-period broadband	vertical triaxial
PV05	38.15	108.97	2142	5/83-7/16/15 5/10-present	short-period broadband	vertical triaxial
PV06	38.33	108.46	2243	5/83-8/94	short-period	vertical
PV07	38.44	108.64	2040	6/83-8/27/11 5/10-present	short-period broadband	vertical triaxial
PV08	38.58	108.65	2950	6/83-9/89 9/89-10/03 10/07-7/12/11	short-period short-period short-period	triaxial vertical triaxial
PV09	38.50	109.13	2662	6/83-7/16/15	short-period	vertical
PV10	38.29	109.04	2266	6/83-7/16/15 10/08-present	short-period broadband	vertical triaxial
PV11	38.30	108.87	1882	12/89-10/13 10/08-present	short-period broadband	triaxial triaxial
PV12	38.32	108.80	2092	12/89-7/05 11/05-present	short-period broadband	vertical triaxial
PV13	38.16	108.82	2158	12/89-7/16/15 5/10-present	short-period broadband	vertical triaxial
PV14	38.37	109.02	2234	12/89-4/02 6/07-present	short-period broadband	vertical triaxial
PV15	38.34	108.48	2234	6/95-8/27/11 7/11-present	short-period broadband	vertical triaxial
PV16	38.31	108.92	2025	7/99-7/16/15 5/10-present	short-period broadband	vertical triaxial
PV17	38.28	108.96	1991	11/05-present	broadband	triaxial
PV18	38.25	108.91	1999	7/11-present	broadband	triaxial
PV19	38.31	108.98	2041	7/11-present	broadband	triaxial
PV20	38.34	108.97	1852	7/11-present	broadband	triaxial
PV21	38.56	108.97	2235	7/11-present	broadband	triaxial
PV22	38.54	108.79	1925	7/11-present	broadband	triaxial

Station Name	Latitude deg., N	Longitude deg., W	Elev. m	Dates of Operation	Station Type	Sensor Direction
PV23	38.45	109.01	2456	11/11-present	broadband	triaxial
PVPP	38.30	108.90	1524	12/97-present	strong motion	triaxial
PVEF	38.33	108.85	1513	10/03-present	strong motion	triaxial
PVCC	38.37	108.96	1617	6/05-present	strong motion	triaxial

Notes: Elevations are relative to mean sea level (MSL). The surface elevation of the injection well is 1540 m above MSL. Stations with vertical sensor direction are single-component; triaxial are 3-component (vertical, north, and east).

Table II-2: Location Names of PVSN Seismic Stations

Station	Station Location Name
PV01	The Burn
PV02	Monogram Mesa
PV03	Wild Steer
PV04	Carpenter Flats
PV05	E. Island Mesa
PV07	Long Mesa
PV08	Uncompahgre Butte
PV09	North LaSalle
PV10	Wray Mesa
PV11	Davis Mesa
PV12	Saucer Basin
PV13	Radium Mtn
PV14	Lion Creek
PV15	Pinto Mesa
PV16	Nyswonger Mesa
PV17	Wray Mesa East
PV18	Skein Mesa
PV19	Morning Glory Mine
PV20	W. Nyswonger Mesa
PV21	Cone Mountain
PV22	Blue Mesa
PV23	Carpenter Ridge
PVPP	Paradox Valley Pumping Plant
PVEF	Paradox Valley Extraction Field
PVCC	Paradox Valley Community Center

Upgrade and expansion of the original 10-station continuously telemetered, high-gain seismic network began in 1989. First, a three-component station (PV11) was installed on the mesa just south of the injection well to provide better focal depth control and to allow for more sensitive event detection. Three vertical-component stations (PV12-PV14) were added in 1989 to increase the density of stations surrounding the well. Station PV08 was downgraded in 1989 from a three-component station to a vertical-component-only station because it was determined that the equipment could be better used at the new stations closer to the injection well. Station PV15 was installed in 1995 to replace PV06, which had been vandalized in 1991, 1992, and 1994, when it was finally abandoned. A second three-component station (PV16) was installed on the mesa north of the injection well in 1999 to further improve near-well coverage.

In October 2000, a major upgrade to the data telemetry and acquisition was implemented. Up until this time, analog data from all stations had been radio-telemetered through PV08, which then relayed the data stream to Reclamation offices in Montrose, where it was transmitted via microwave and analog telephone links to Denver. In Denver, the analog data from all stations were digitized (using 12-bit digitizers) and processed. In October 2000, a wide-area network (WAN) link was established at the Hopkins Field Airport, near Nucla, Colorado, and new 16-bit digitizers were installed there. All analog radio links from the stations were reconfigured to terminate at Hopkins Field, and the use of analog telephone circuits to relay data was discontinued. Station PV08 was no longer used as a radio-telemetry relay. Station PV08 was temporarily removed in October 2003 to accommodate nearby construction activities and reinstalled in October 2007, at which time it was returned to a three-component configuration.

Starting in 2005, upgrades to the high-gain seismic network focused on replacing the analog short-period seismic instrumentation with digital broadband instrumentation. The short-period instrumentation had become obsolete, both in terms of the data quality needed for ongoing analyses and in terms of maintaining equipment that was no longer manufactured. Two key characteristics of the instrumentation constrain data quality: bandwidth and dynamic range. The short-period instrumentation had an effective seismic signal bandwidth of 1-20 Hz. The low end of this range was determined by the natural frequency (1 Hz) of the seismometers used (Geotech model S-13), and the high end by the analog low-pass filter setting (nominally 25 Hz). The bandwidth of the analog stations was insufficient for many analysis purposes, such as accurately identifying complex seismic phases, accurately computing seismic moments of induced earthquakes (which require determination of long-period spectral levels), waveform modeling, or extracting time-domain Green's functions from ambient noise. Furthermore, the effective dynamic range of the analog stations constrained the ratio of the largest to smallest seismic signal that could be recorded on-scale to only a factor of about 1000, which corresponds to approximately two earthquake magnitude units. This resulted in seismic signals of earthquakes greater than about M 1.5 being clipped, which limited the use of this important data for magnitude and moment calculations, waveform cross-correlation, and identification of the S-wave arrival. Although 16-bit digitizers (with a dynamic range of 90 dB) were used after 2000, the effective dynamic range of the analog stations remained much less, approximately 10 or 11 bits (60 dB), because of the limited sensitivity of the voltage-controlled oscillators (VCOs) used at the stations to modulate the seismic signals onto the carrier tones used for analog radio telemetry. Modern broadband instrumentation provides much better characteristics, with typical bandwidths of 0.03 to 50 Hz, 24-bit digitizers providing a dynamic range of 135 dB or more, and seismometers typically packaged as a single unit with internal three-component sensors.

In November 2005, the first three-component broadband seismometer (Guralp model CMG-40TD) was installed at a new station southwest of the injection well (PV17). This instrument uses a 24-bit digitizer integrated within the seismometer case to minimize potential cable noise (digitizers and seismometers separated by a long analog cable can be sensitive to cross-talk at the microvolt level, which is difficult to protect against). Station PV12 was similarly upgraded at about the same time, and stations PV04 and PV14 were converted in May and July of 2007. These first-generation digital stations used digital radios that effectively behaved as a remote RS232 serial data link and which required the use of “combiner-repeater” modules (Guralp model CRM-6) to combine the serial signals from multiple stations. The first-generation stations exhibited a number of data quality problems, the most severe of which was crosstalk between the GPS antenna cabling (which provided timing for the internal digitizer) and the system providing power to the seismometer (O’Connell, 2008). The crosstalk inherent in the first-generation design resulted in significant spectral spikes in the data at frequencies of 1 Hz and greater, as illustrated in Figure II-7.

A new station design was developed in 2007 and 2008 based on experience from the first generation stations and from similarly instrumented seismic networks deployed at B.F. Sisk and Hungry Horse Dams (O’Connell, 2008). The new stations incorporated features to minimize the GPS antenna cable crosstalk problem, as well as to make the system more modular and robust. It included entirely new seismometer vaults, station enclosures, antennas, solar panels, and Ethernet packet radios. Deployment of the new instrumentation began in 2008, with upgrades of PV02, PV03, PV10, and PV11. In May 2010, stations PV01, PV05, PV07, PV13, and PV16 were upgraded. In July 2011, station PV15 was upgraded. In addition, six broadband digital seismic stations (PV18 to PV23) were installed at new sites in 2011. Two of these stations, PV22 and PV23, are replacements for old analog stations PV08 and PV09, which were decommissioned because they were noisy sites founded on thick alluvial deposits (all other sites are on rock). The other four new seismic stations (PV18, PV19, PV20, and PV21) were installed to improve coverage in seismically active areas of interest (including seismicity occurring within 9 km of the injection well and at the northern end of Paradox Valley).

The digital broadband upgrade of PVSN seismic stations was completed in late 2011. Consequently, Reclamation discontinued maintenance of the obsolete analog seismic stations. Four of those stations permanently went offline during 2011 (PV02, PV07, PV08, and PV15), and an additional analog station (PV11) ceased functioning in late 2013. The remaining analog stations were decommissioned in July 2014, when the data acquisition center at Hopkins Field was relocated into a new building.

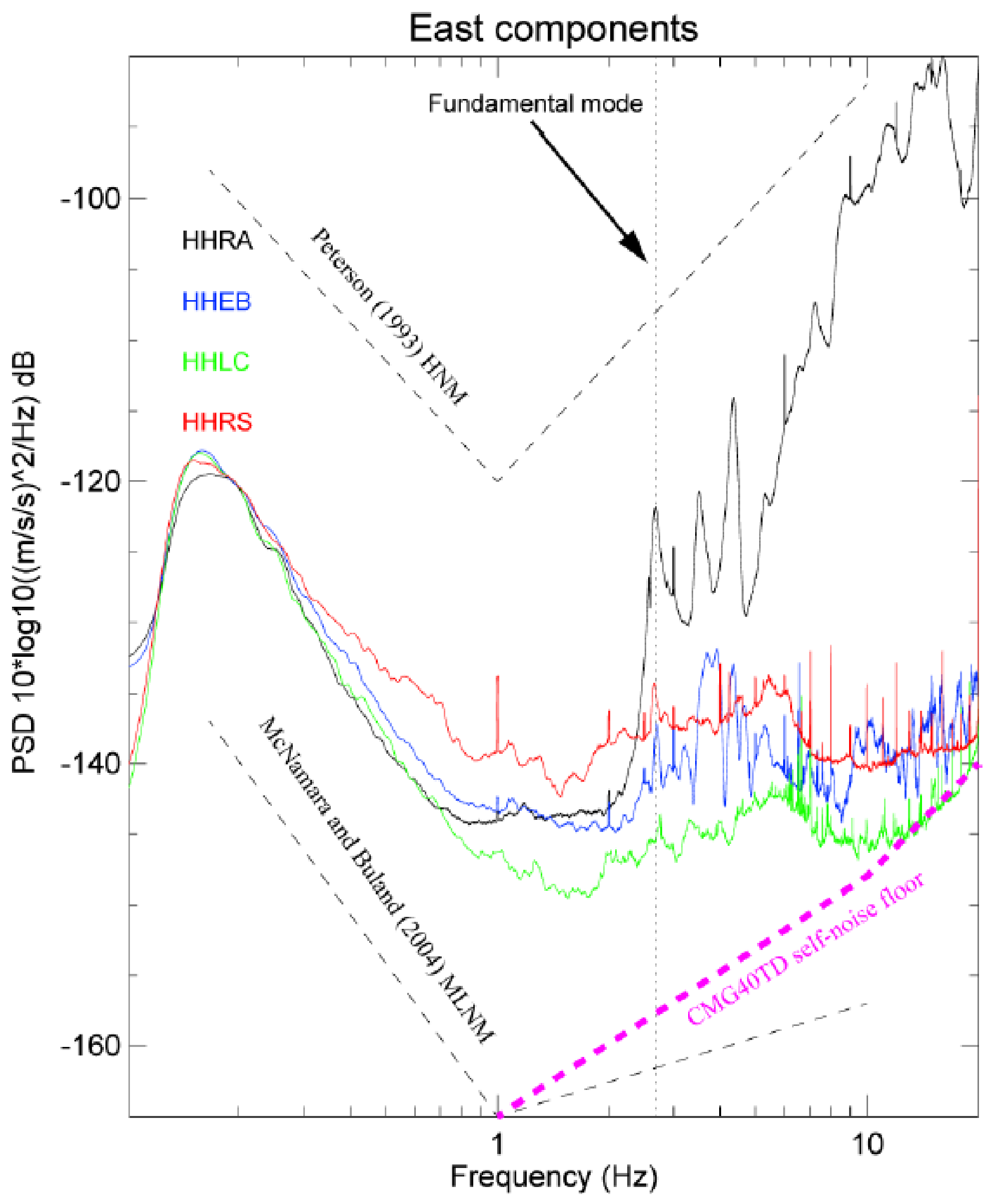


Figure II-7: Stacked multi-taper acceleration power spectra from the east-west components of Guralp model CMG40TD seismometers installed at four first-generation stations (HHRA, HHEB, HHLC, and HHRS) near Hungry Horse Dam, Montana. Windows were 400 seconds in length and represented ambient conditions. (Station HHRA was located close to the power generation plant at the dam, and therefore exhibited much higher ambient noise levels at frequencies above 2 Hz.) The obvious spikes in the spectra at frequencies of 1 Hz and higher were caused by GPS antenna crosstalk problems inherent in the first-generation stations. A new station design was implemented at PVSN to substantially reduce these crosstalk problems. Figure from O'Connell (2008).

During 2018, we began the replacement of the Guralp model CMG-40TD broadband seismometers with Guralp model 3ESPCDE seismometers, as some of the original seismometers began to fail and were no longer supported. For example, compatible GPS antennas could no longer be obtained for the oldest CMG-40TDs in the network, making continued maintenance of the stations with these old instruments impractical. The 3ESPCDE seismometers have several advantages over the CMG-40TD seismometers, including substantially less self-noise, considerably less power usage than the oldest CMG-40TDs, and Ethernet capability for future communications upgrades. In April 2018, the CMG-40TD seismometers at stations PV02, PV10, PV18, PV20, and PV23 were replaced with new 3ESPCDE seismometers. The seismometers at stations PV12 and PV19 were upgraded in May 2019. The seismometers at the remaining stations were upgraded in September 2020 (PV03, PV04, PV05, PV11, PV13, PV14, PV15, PV17, PV21, PV22) and October 2020 (PV01, PV07, PV16).

In addition to the continuously telemetered high-gain seismic array, three event-triggered strong-motion instruments were added to PVSN. The first strong-motion instrument (PVPP) was installed near the PVU injection wellhead in December 1997. A second strong-motion instrument was installed near the PVU extraction facilities (PVEF) in January 1998, and the third was installed at the nearby community of Paradox, Colorado (PVCC) in June 2005. Telemetry for the strong-motion instruments was provided by dial-up phone lines. The strong-motion array is designed to measure earthquake ground motions that are large enough to be felt or cause damage and which could saturate high-gain array stations closest to the epicenter.

The original instruments at PVPP and PVEF consisted of 12-bit data loggers (Kinemetrics model SSA-2 and Syscom model MR2002) and three-component force-balance accelerometers (FBAs), with the digitizers only approximately synchronized to Coordinated Universal Time (UTC). In November 1999, station PVEF was upgraded to use an 18-bit digitizer (Kinemetrics model K2), which was synchronized to UTC using a GPS receiver. Station PVPP was similarly upgraded in October 2003. Station PVCC had used a K2 data logger since its original installation in 2005.

On February 28, 2019, the K2 was removed from station PVEF, and three different data loggers and accelerometers were installed for a temporary side-by-side comparison study. These included the following instruments: (1) Reftek model RT130 data logger with Silicon Audio model 203V accelerometer, (2) Reftek RT130 data logger with Nanometrics model Titan accelerometer, and (3) Guralp model Minimus data logger with Guralp model Fortis accelerometer. A wireless TCP/IP bridge was installed to provide continuous real-time radio telemetry. In May 2019, the Silicon Audio sensor and Reftek digitizer were removed, and the Titan sensor was replaced with a similar unit with an internal digitizer. From May 2019 to October 2020, the Guralp instruments and the Nanometrics Titan with internal digitizer were run side-by-side at PVEF with continuous telemetry.

Following the testing of strong motion sensors and digitizers in 2019-2020, the decision was made to upgrade all strong motion sites using a Silicon Audio model 203V accelerometer and a Guralp Minimus digitizer. These upgrades were implemented in October 2020. At the same time, real-time radio telemetry was established for stations PVPP and PVCC. The real-time data from all three strong motion sites are integrated with the data from the high-gain broadband sites at the PVSN communication center at Hopkins Field in Nucla, Colorado.

2. Induced Seismicity

More than 11,100 relatively shallow (≤ 10 km deep) earthquakes have been recorded in the vicinity of Paradox Valley since injection began in 1991. No shallow earthquakes were detected in six years of seismic monitoring prior to the start of injection operations. Most of these events have focal depth estimates between approximately 2.5 and 6.5 km (relative to the ground surface elevation at the PVU injection wellhead), close to the depth of the injection interval (4.3 to 4.8 km). The seismicity has been observed at increasing distance from the injection well over time (Figure II-8). The initial earthquakes were detected just four days after the start of the first injection test in July 1991 and occurred very close to the injection well. As injection continued, earthquakes occurred at progressively increasing radial distances. By 2002, earthquakes were occurring as far as 16 km from the well. The lack of shallow seismicity detected during six years of pre-injection seismic monitoring, the general correlation of the depths of the earthquakes and the depth of injection, and the spatiotemporal evolution of the seismicity since the start of injection demonstrated in Figure II-8 indicate that these earthquakes have been induced by PVU fluid injection.

Several distinct groups, or clusters, of induced seismicity have developed over the history of PVU injection operations. By the end of the injection tests in 1995, earthquakes were occurring to radial distances of roughly 4 km from the well (Figure II-9a). This area of induced seismicity immediately surrounding the injection well is referred to as the “near-well” region. In 1997, about one year after the start of continuous injection, earthquakes began occurring 6 to 8 km northwest of the injection well (Figure II-9b). This group of induced seismicity is called the “northwest (NW) cluster”. In mid-2000, earthquakes were first detected 12 to 14 km from the injection well, along the northern edge of Paradox Valley (Figure II-9b). Several distinct clusters of earthquakes soon formed along the northern edges of the valley (Figure II-9c). The earthquakes occurring in all these groups are referred to as “northern valley events”. Following the formation of these clusters (and a 32% decrease in the injection rate in mid-2000), the geographical expansion of induced seismicity greatly slowed for nearly a decade (Figure II-9c, d) but was renewed in 2010. For example, a single earthquake was first detected about 6 km southeast of the injection well in 2004 (Figure II-9c), but the seismicity rate in this area markedly increased beginning in 2010 (Figure II-9e). This tight group of earthquakes is referred to as the “southeast (SE) cluster”. Earthquakes also began occurring in north-central Paradox Valley in 2010. (Figure II-9e). In the last several years, the rate of induced seismicity at the northern end of Paradox Valley has increased, and its geographical extent has expanded (Figure II-9e, f, g, and h). Earthquakes likely related to

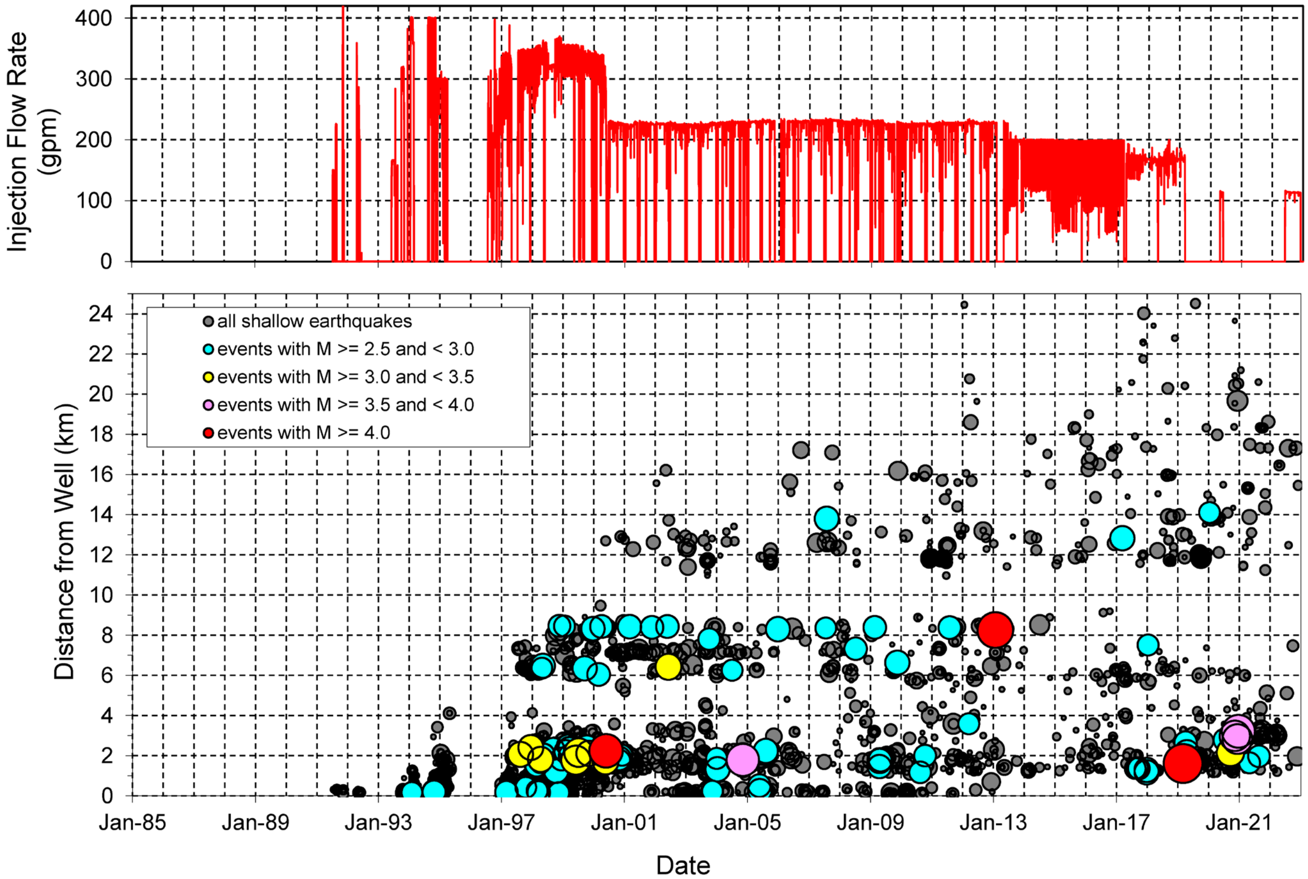


Figure II-8: Lower plot: scatter plot of earthquakes having magnitude ≥ 0.5 and depth ≤ 10 km (relative to the ground surface elevation at the injection wellhead), plotted as a function of date and distance from the PVU injection well. Each circle represents a single earthquake, with the width of the circle scaled by the event magnitude. The magnitudes shown are duration magnitudes for earthquakes with M_D < 3.0 and moment magnitudes for larger events. Upper plot: daily average injection flow rate.

PVU brine injection are now occurring at distances up to ~27 km northwest of the injection well and up to ~7 km outside the northwest perimeter of the seismic network (Figure II-9g). In addition, seismicity potentially related to PVU brine injection has occurred in several previously aseismic areas, including: toward the southeast to a distance of ~37 km from the injection well, east to a distance of ~24 km from the well, and west to a distance of ~14 km from the well (Figure II-9f, g, h).

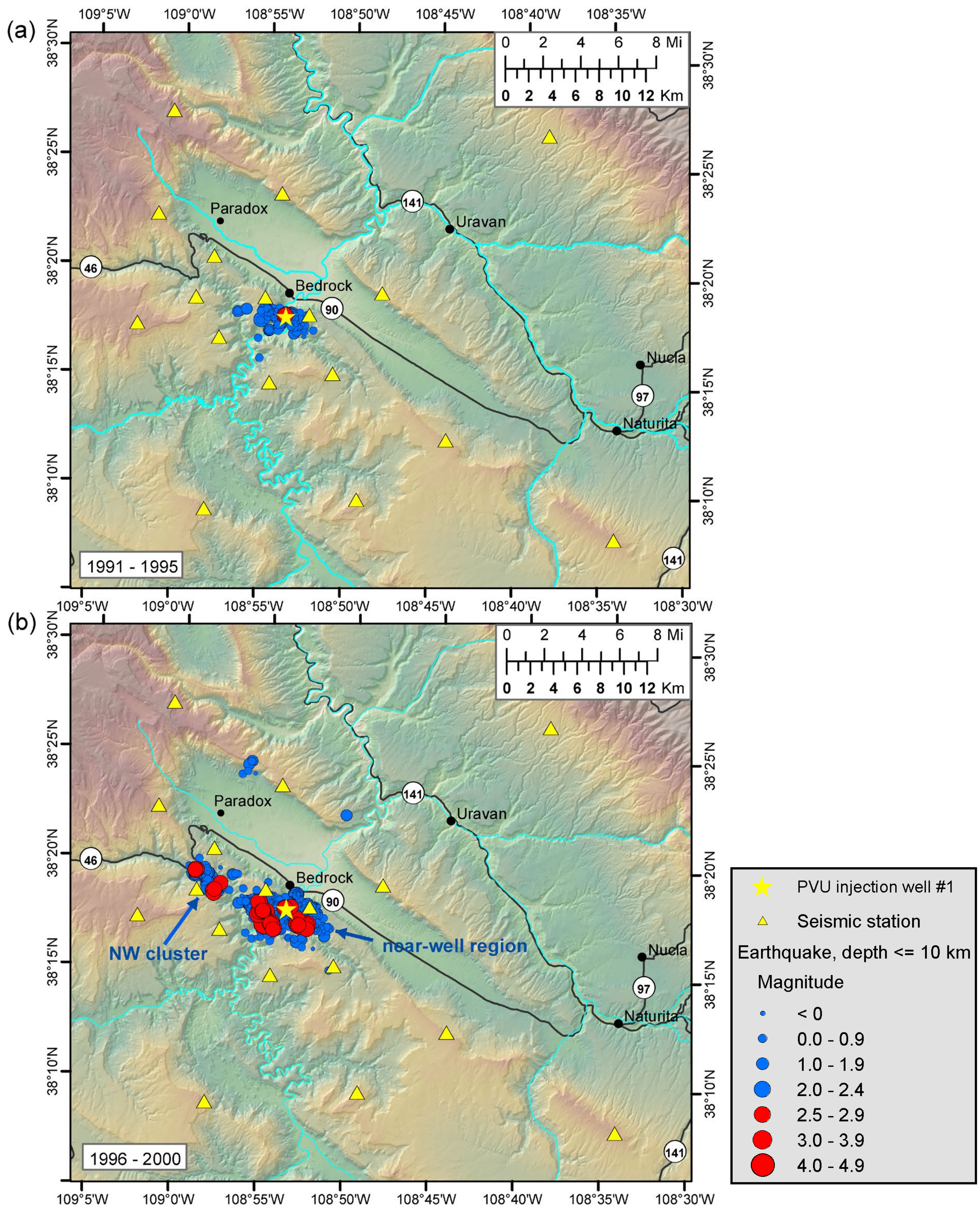
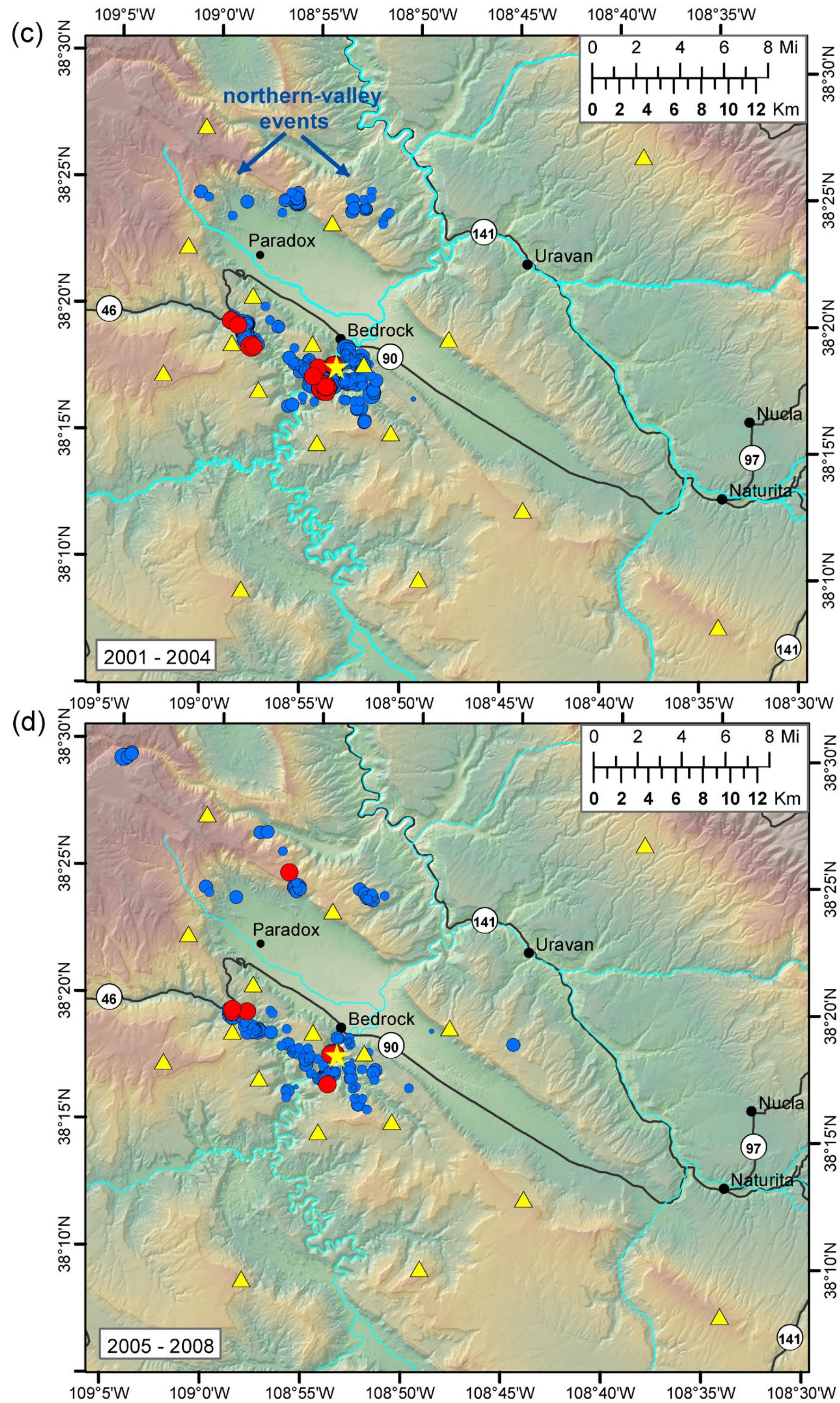
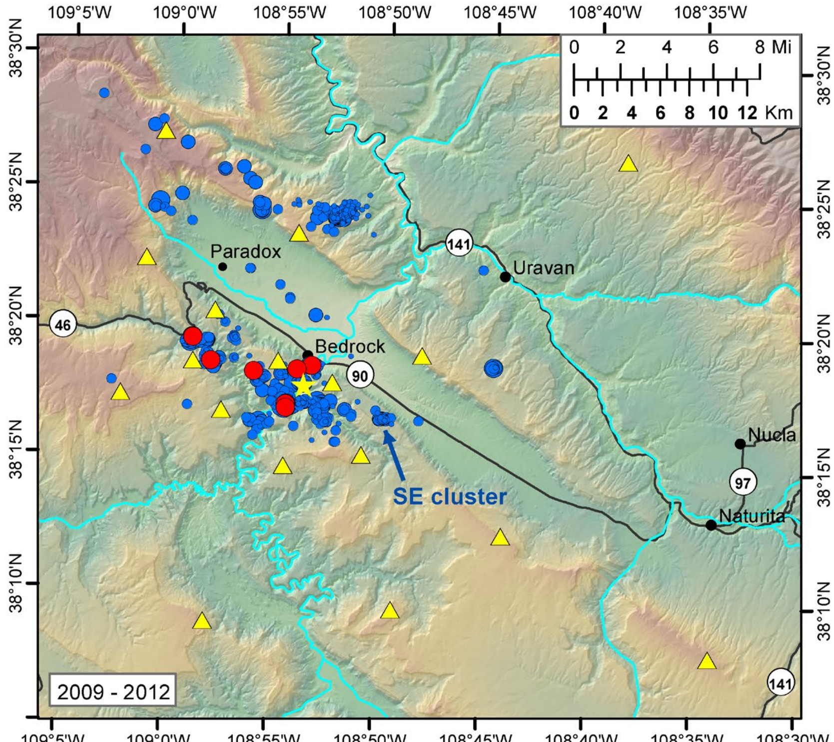


Figure II-9: Maps showing the spatial distribution of shallow seismicity (depth ≤ 10 km) over time: (a) 1991-1995 (b) 1996-2000 (c) 2001-2004 (d) 2005-2008 (e) 2009-2012 (f) 2013-2016 (g) 2017-2019 (h) 2020-2022. Earthquake symbols are sized according to magnitude, and earthquakes with magnitudes ≥ 2.5 are shown in red.


(c)
northern-valley events
Paradox
Uravan
Bedrock
Nucla
Naturita
141
46
90
97
0 2 4 6 8 Mi
0 2 4 6 8 10 12 Km
109°5'W 109°0'W 108°55'W 108°50'W 108°45'W 108°40'W 108°35'W 108°30'W
38°30'N 38°25'N 38°20'N 38°15'N 38°10'N
2001 - 2004
(d)
2005 - 2008

(e)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Paradox
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Bedrock
Nucla
Naturita
SE cluster
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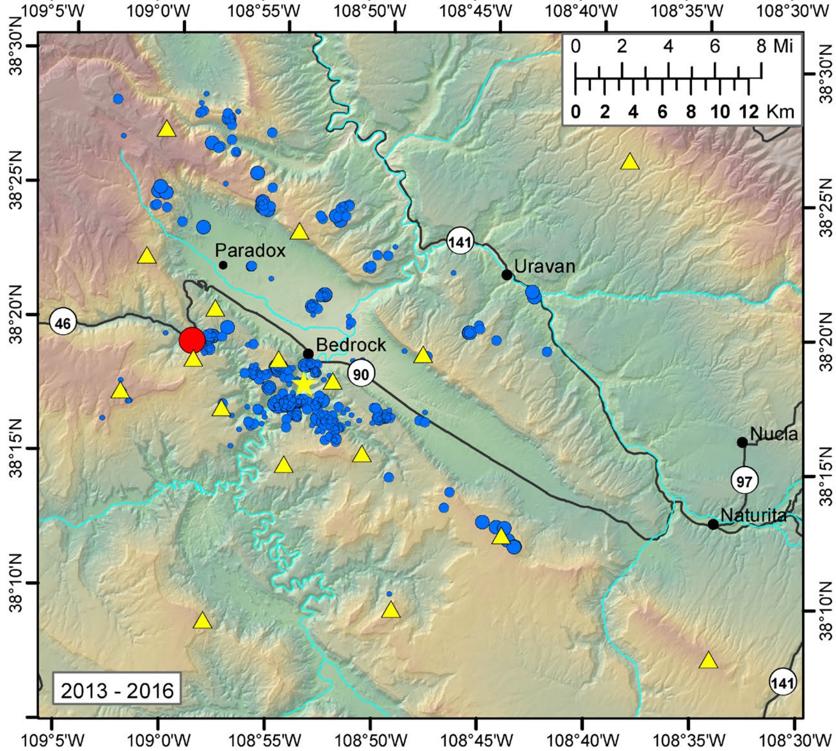
109°5'W
109°0'W
108°55'W
108°50'W
108°45'W
108°40'W
108°35'W
108°30'W
38°30'N
38°25'N
38°20'N
38°15'N
38°10'N

(f)


0 2 4 6 8 Mi
0 2 4 6 8 10 12 Km
Paradox
Uravan
Bedrock
Nucla
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109°0'W
108°55'W
108°50'W
108°45'W
108°40'W
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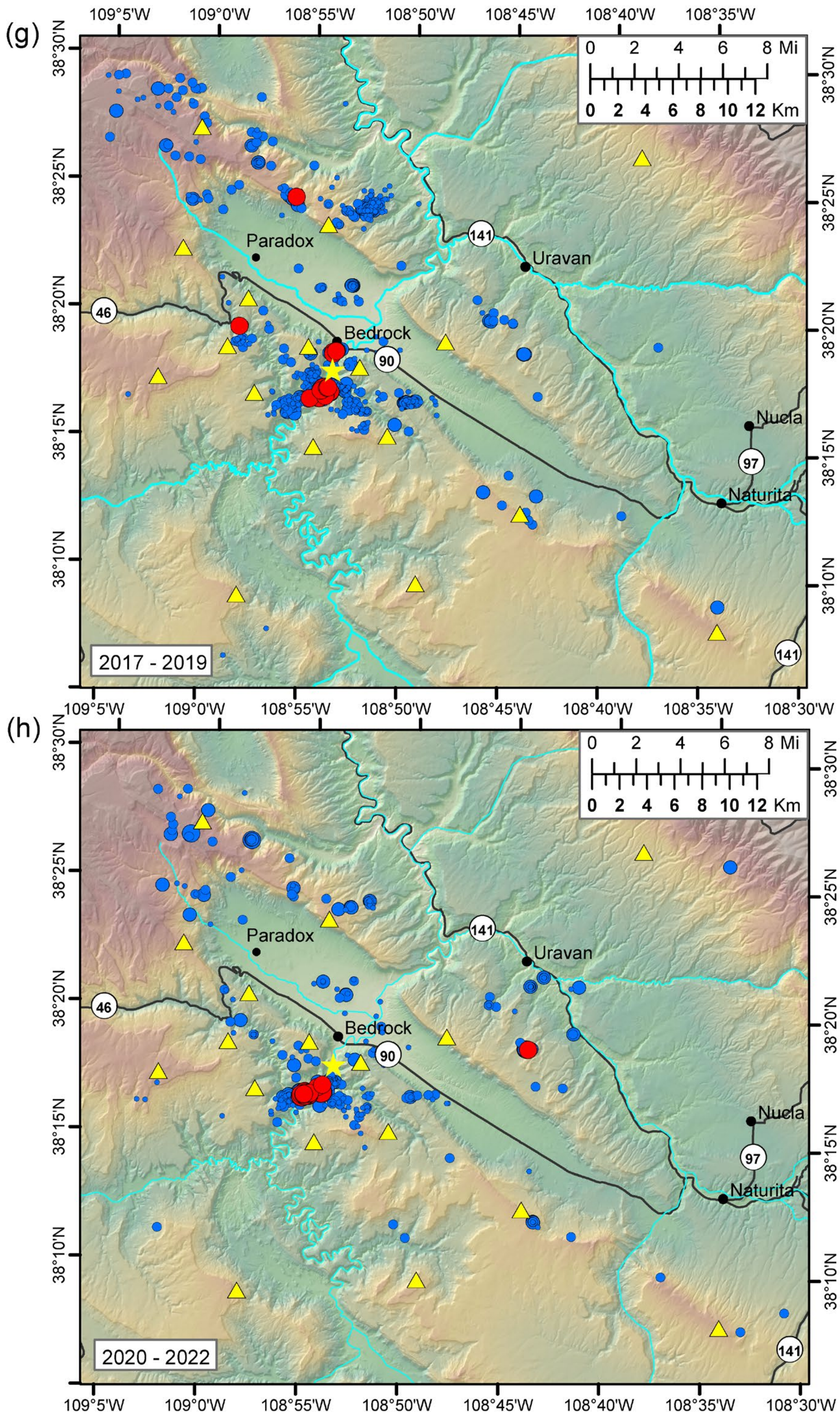
108°30'W
38°30'N
38°25'N
38°20'N
38°15'N
38°10'N


(g)
109°5'W
109°0'W
108°55'W
108°50'W
108°45'W
108°40'W
108°35'W
108°30'W
38°30'N
38°25'N
38°20'N
38°15'N
38°10'N
0 2 4 6 8 Mi
0 2 4 6 8 10 12 Km
Paradox
Uravan
Bedrock
Nucla
Naturita
141
46
90
97
2017 - 2019
(h)
2020 - 2022

III. Network Operations during 2022

A. Network Maintenance and Upgrades

Two site visits were conducted in 2022. During these site visits, preventive and remedial maintenance was performed at 19 of the 20 remote broadband seismic stations, the three strong motion sites, and the data communication center at Hopkins Field in Nucla, Colorado. The remaining broadband seismic station (PV16) was not visited during 2022 because a planned trip for late fall 2022 to service this site via helicopter was cancelled when the helicopter purchase request could not be completed in time. The helicopter trip to PV16 will be rescheduled for 2023. A summary of the activities performed at the sites during 2022 is given below. Additional details of the work performed at each site are included in the site visit reports in Appendix A.

The preventive maintenance performed at the seismic stations included: checking station power systems, replacing aging batteries, testing cables and antennas and replacing any degraded components, testing radios, and inspecting seismometer vaults. Remedial maintenance included replacing drained batteries, radio cable, DM24-BOB, and antenna cables.

In addition to the routine maintenance activities listed above, a shattered glass plate was discovered during seismic vault inspection at station PV10. Cable damage from bears was found at several stations, and hog wires were installed at PV13, PV15, PV17, and PV23 to help prevent future damage. Open-circuit unloaded solar panel testing showed unsatisfactory results (< 20V) in full sun at PV01, PV12, PV19, PV20, PV22, and PV23, where all panels showed signs of discoloration. Specialized testing equipment is being purchased so that more accurate measurements of solar panel performance can be performed in 2023. Weather stripping was installed behind the entry door of the station enclosure at PVCC. During these field inspections, it was noted that grounding work has yet to be completed at stations PV03, PV10, and PV18.

At the Hopkins Field communication center, routine equipment testing was performed. Unfortunately, antenna testing was unsuccessful due to interference on radio signals from an unidentified source that prevented accurate measurements. Two new switches were brought to the shelter (for later installation). A new external hard drive was successfully installed for data backup. The older external hard drive was brought back to Denver to retrieve archived data.

B. Network Performance

PVSN network performance depends on the performance of the hardware at individual seismic stations, the robustness of the radio data communication between the stations and the communication hub at Hopkins Field, and the reliability of the data acquisition computer systems. The performance of each of these components during 2022 is discussed below.

The PVSN broadband seismic stations experienced very few hardware problems in 2022 (Table III-1). The only station that experienced major hardware problems was station PV18, which was offline for five months from December 10, 2021 to May 5, 2022 (Figure III-1). The station was brought back online after its DM24-BOB was replaced during a site visit in May 2022. However, the station began experiencing other problems (GPS timing failures and seismometer reboots) in late November 2022 and went offline again in February 2023. Another site visit is required to further diagnose and repair this station. GPS timing at station PV12 has been intermittently lost for hundreds of very brief periods during each of the last four winters (since Oct. 2019), most likely due to reboots of its GPS antenna. Diagnostic tests have been performed several times and various components have been replaced, but the issue currently remains unresolved. In the meantime, station PV12 is otherwise operating normally and providing useable data.

The three strong motion sites did not experience any substantial hardware problems during 2022. However, strong motion station PVPP was mostly offline from November 22nd to December 6th due to a radio malfunction, resulting in an uptime for November of 72% (Figure III-1). Station PVEF was offline for two periods during March: on March 14th for about three hours and for five days from March 17th to March 22nd. This site receives AC power from the PVU filtration plant, and this plant experienced power outages during these two time periods. Battery backup at the seismic station kept radio communication powered during these outages, but the seismometer was powered down.

Most stations experienced robust radio communications during 2022, which maintained the network's ability to continuously transmit the seismic data. Stations PV07 and PV21 experienced minor data loss, ~2% and ~1%, respectively, due to intermittent, slightly degraded radio communications (Figure III-1).

The PVSN data acquisition computer systems were online and functioning normally throughout the year, other than brief interruptions for routine PVSN preventive maintenance. Stations PVEF and PVPP became disconnected from the *Scream* seismic data acquisition software for separate brief periods in July 2022 (Figure III-1) but were manually reconnected and subsequently remained online.

The two servers in PVSN's data communication center at Hopkins Field in Nucla, Colorado, are past their serviceable life. New servers were purchased three years ago, but the deployment of the servers has been delayed because of the long wait time to upgrade the network connection between Nucla and Denver and install and test the required software. Lumen upgraded the network connection to 9.2 Mbps (using multiple T1 lines) in early 2022, and the Paradox Valley Unit project worked with the Nucla-Naturita Telephone Company to install a fiber optic cable to the site in mid to late 2022. We are currently waiting on Lumen to provide a fiber optic router before the new service can be activated. The seismic data acquisition software has been installed on the new servers, and testing is in progress.

Table III-1: Performance of PVSN Seismic Stations During 2022

Station	Performance
PV01	Online and functioning normally throughout the year.
PV02	Online and functioning normally throughout the year.
PV03	Online and functioning normally throughout the year.
PV04	Online and functioning normally throughout the year.
PV05	Online and functioning normally throughout the year.
PV07	Online and functioning normally throughout the year.
PV10	Online and functioning normally throughout the year.
PV11	Online and functioning normally throughout the year.
PV12	Online and mostly functioning well. This station experienced nearly 300 very brief GPS timing failures during January – early May and late October - December, most likely due to reboots of the GPS antenna. These reboots appear to be related to a temperature-sensitive hardware problem.
PV13	Online and functioning normally throughout the year.
PV14	Online and functioning normally throughout the year.
PV15	Online and functioning normally throughout the year.
PV16	Online and functioning normally throughout the year.
PV17	Online and functioning normally throughout the year.
PV18	Went offline in mid-December 2021. A site visit was conducted on May 5, 2022, and the station was brought back online after replacing the DM24-BOB. The station subsequently began experiencing numerous GPS timing failures in late November and seismometer reboots in early December. These problems continued for the rest of 2022 and into 2023.
PV19	Online and functioning normally throughout the year.
PV20	Online and functioning normally throughout the year.
PV21	Online and functioning normally throughout the year.
PV22	Online and functioning normally throughout the year.
PV23	Online and functioning normally throughout the year.
PVEF	Online and functioning normally during most of the year. Offline due to an AC power failure for 3 hours on March 14th and for 5 days from Mar. 17th – 22nd.
PVPP	Online and functioning normally during most of the year. Offline from November 22nd to December 6th due to a radio malfunction.
PVCC	Online and functioning normally throughout the year.

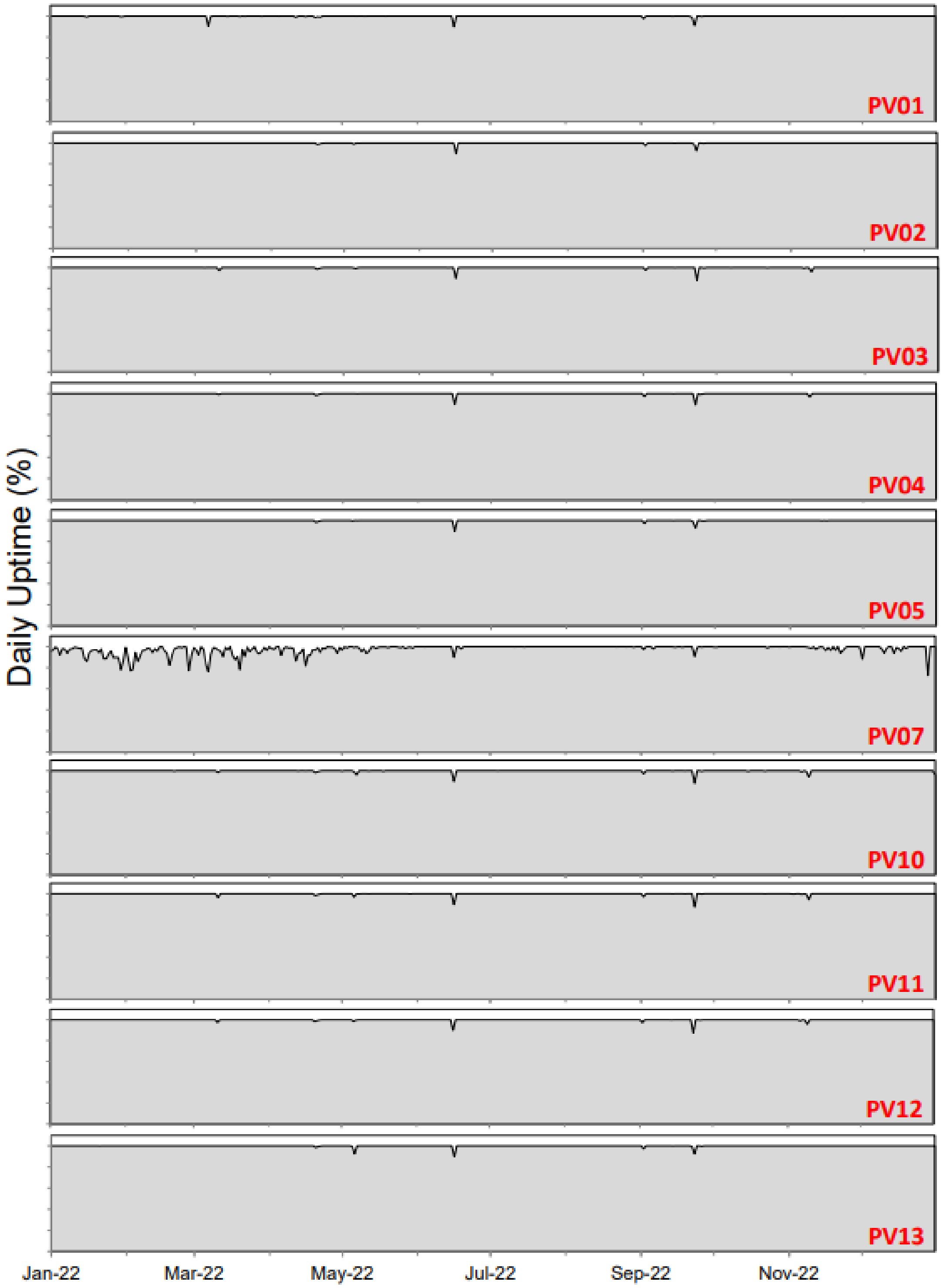


Figure III-1: Daily uptime (%) for the PVSN seismic stations during 2022. The uptime values represent the percent of the day for which data from a given station were recorded. The vertical axes on the plots are scaled from 0 to 110%. Filled gray areas represent daily uptime, while dips in the filled volume show decreases in uptime (lack of data).

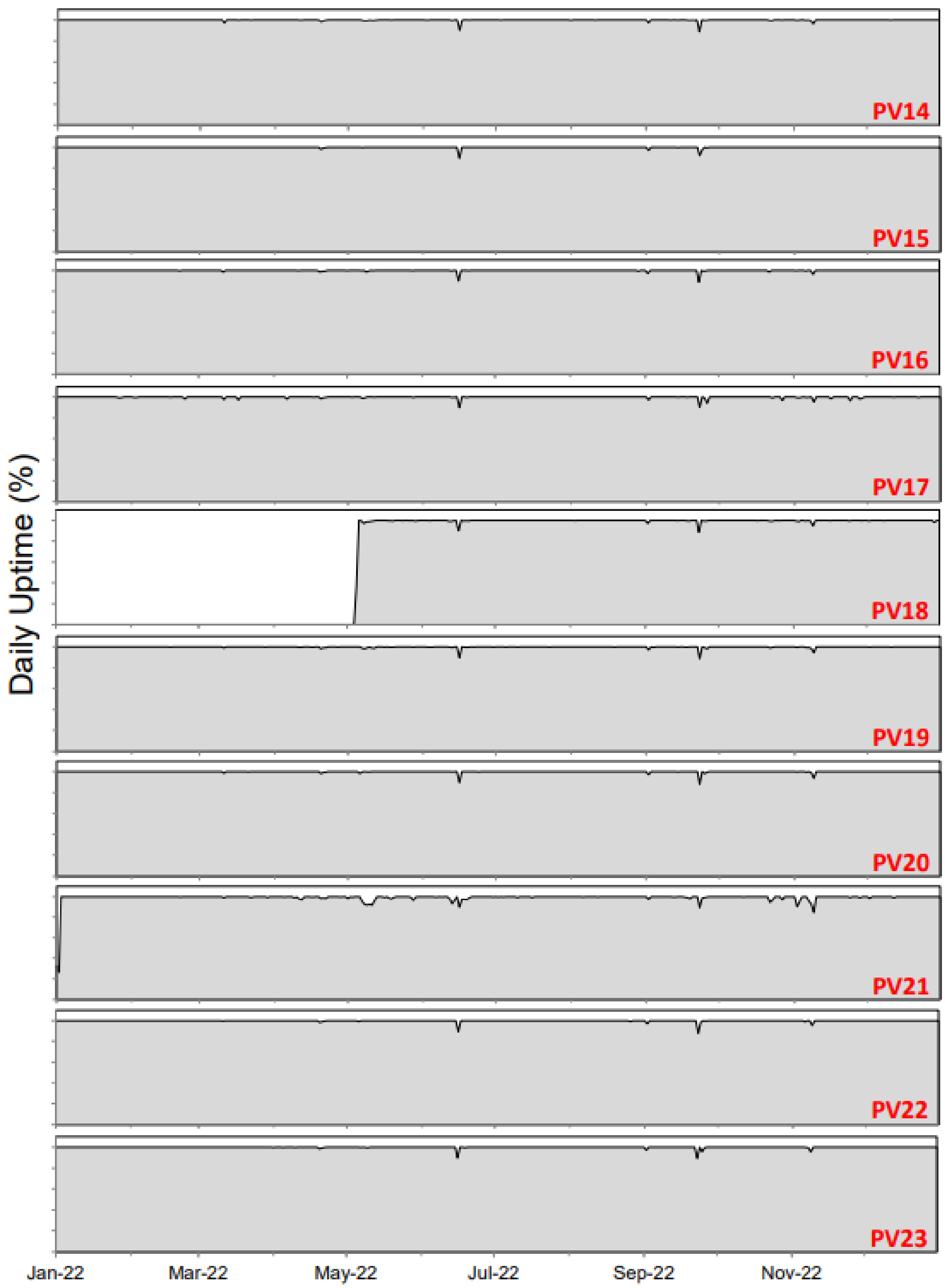


Figure III-1, continued.

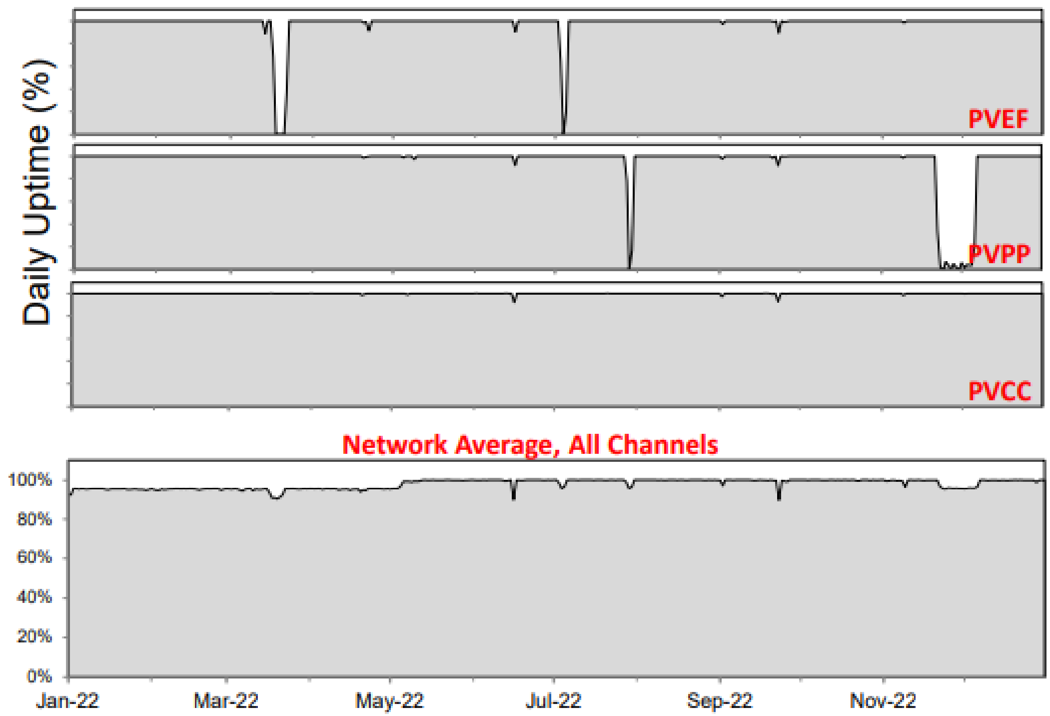


Figure III-1, continued. The bottom plot shows the daily average performance for all PVSN channels.

Considering data loss from hardware failures at individual seismic stations, radio communication data drop-outs, and PVSN system downtimes, the 2022 annual uptimes for the PVSN broadband and strong motion seismic stations range from 66% to 100%, with 21 of the 23 stations having uptimes ≥ 98% (Figure III-2; Table III-2). These uptimes represent the percent of the year for which data from a given station were recorded.

We have been computing and tracking the overall annual uptimes of PVSN since 2000. These annual uptimes are estimates of the percent of each year during which PVSN was reliably detecting and recording earthquakes. They generally represent the percent of the year during which the PVSN data acquisition systems were operating. In 2022, there were no significant time periods when the entire seismic network was offline. Overall, the annual PVSN uptime for 2022 was still 100.0% (rounded to the nearest 0.1%, Table III-3).

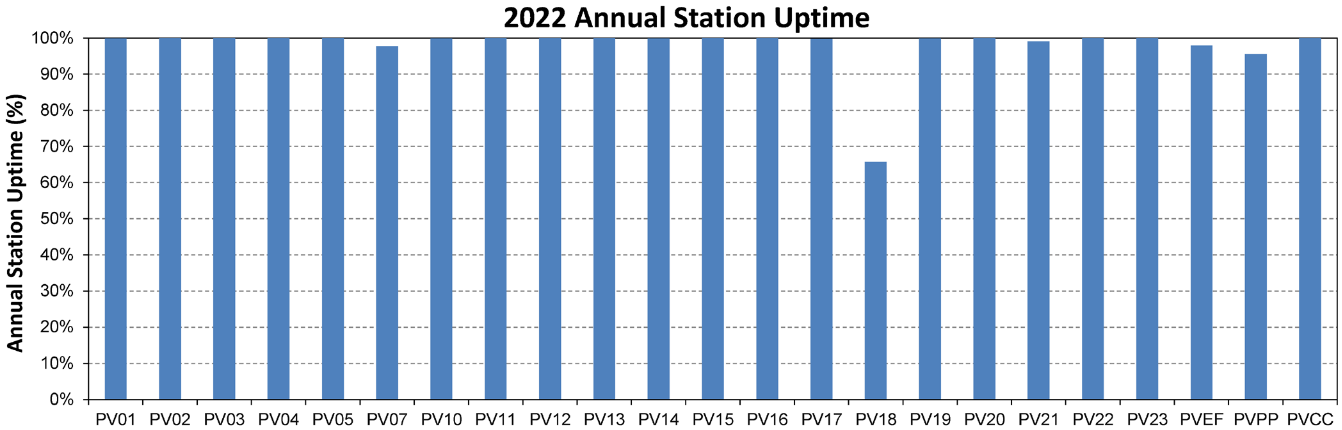


Figure III-2: Graph of annual (2022) uptime for each PVSN seismic station.

Table III-2: Annual PVSN Station Uptimes in 2022

Station	Annual Station Uptime
PV01	100%
PV02	100%
PV03	100%
PV04	100%
PV05	100%
PV07	98%
PV10	100%
PV11	100%
PV12	100%
PV13	100%
PV14	100%
PV15	100%
PV16	100%
PV17	100%
PV18	66%
PV19	100%
PV20	100%
PV21	99%
PV22	100%
PV23	100%
PVEF	98%
PVPP	95%
PVCC	100%

Table III-3: Annual PVSN Uptimes

Year	Annual Number of Days with Monitoring Absent or Substantially Degraded	Percent Uptime
2000	24	93.4%
2001*	**	**
2002	5	98.6%
2003	14.5	96.0%
2004	16	95.6%
2005	34	90.7%
2006	47	87.1%
2007	37	89.9%
2008	10	97.2%
2009	6.5	98.2%
2010	0	100.0%
2011	12.2	96.7%
2012	2.2	99.4%
2013	4.6	98.8%
2014[1]	10.3	97.2%
2015[2]	8.7	97.6%
2016[3]	17.3	95.3%
2017[4]	1.2	99.7%
2018	2.4	99.3%
2019	0.03	100.0%
2020	2.3	99.4%
2021	0.1	100.0%
2022	0.03	100.0%

**not tabulated in 2001

[1] includes 40.5 hours of downtime in September 2014 when the network was operating, but event detection was severely degraded due to malfunctioning of the data acquisition software

[2] includes a 50% rating for 12 days in February and 5 days in December when the network was operating but monitoring was substantially degraded due to the absence of data from 8-12 stations simultaneously.

[3] includes a 50% rating for 9 days in August and 22 days in September when network was operating but monitoring was substantially degraded due to absence of data from 14 stations simultaneously.

[4] includes 50% rating for 31 hours in January when network was operating but monitoring was substantially degraded due to absence of data from ≥ 5 stations simultaneously.

IV. Seismic Data Recorded in 2022

A. Annual Summary

In 2022, 202 earthquakes were recorded within or near the perimeter of PVSN. The map in Figure IV-1 shows the epicenters of these events (colored circles), as well as the epicenters of all earthquakes recorded in previous years (gray and white circles). The local earthquakes are classified into four categories based on their depths (relative to the ground surface elevation of 1.524 km above MSL at the PVU injection well) and distances from the injection well:

1. Shallow near-well: depth ≤ 10 km, distance from the injection well ≤ 5 km
2. Shallow intermediate: depth ≤ 10 km, distance from injection well > 5 km and ≤ 10 km
3. Shallow distant: depth ≤ 10 km, distance from injection well >10 km
4. Deep: depth > 10 km, any distance from the injection well

The earthquakes recorded during 2022 are color-coded using these categories in the map presented in Figure IV-1, and the numbers and magnitudes of the earthquakes in each category are summarized in Table IV-1. The 2022 local earthquake catalog is included in Appendix B.

All but seven of the 202 local earthquakes recorded during 2022 have depths ≤ 10 km. Of these relatively shallow earthquakes, 154 occurred within 5 km of the injection well, 12 occurred at distances between 5 and 10 km from the well, and 29 occurred > 10 km from the well. Based on the relatively shallow depths of these earthquakes and the geographical expansion of the seismicity since injection began, we interpret most, and potentially all, of these earthquakes as being induced by PVU brine injection.

Four of the seven deep earthquakes recorded during 2022 occurred 36 to 41 km north-northwest of the PVU injection well and within a few km of seismic station PV21 (Figure IV-1, purple circles). Estimated depths of these earthquakes are ~14-16 km, relative to the PVU wellhead elevation. PVSN has recorded earthquakes in this area at similar depths since 1999, and we consider these events to be naturally occurring. One of the other deep events recorded during 2022 occurred ~15 km south-southeast of the injection well (near seismic station PV13), at an estimated depth of about 30 km (Figure IV-1). Because of the large depth of this event, we consider it to be naturally occurring. The remaining two deep earthquakes occurred ~18-23 km east of the injection well (Figure IV-1). The closer of these events has a depth estimate of 10.4 km. Earthquakes at similar depths have been observed in this area since 2007. Based on the spatiotemporal evolution of this seismicity, these earthquakes are interpreted as related to PVU injection (Block et al., 2021). The farther of the two events recorded in 2022 in this general area has a depth estimate of almost 16 km (relative to the PVU wellhead elevation). It is both farther from the PVU injection well and a few km deeper than most of the other events in this general area. Its potential relation to PVU injection is unknown.

Table IV-1: Summary of Earthquakes Recorded During 2022 by Location Category

Location Category	Depth	Distance from well	Number of Earthquakes	Number of Earthquakes with $M_D \geq 0.5$	Min. Magnitude[1]	Max. Magnitude[1]
shallow near-well	≤ 10 km	0 to 5 km	154	20	-1.3	2.4
shallow intermediate	≤ 10 km	> 5 to 10 km	12	2	-1.0	1.5
shallow distant	≤ 10 km	> 10 km	29	9	-1.2	2.0
Deep	> 10 km	all distances, within or near the perimeter of PVSN	7	4	-0.7	1.0
TOTAL SHALLOW	**≤ 10 km**	**all**	**195**	**31**	**-1.3**	**2.4**
TOTAL	**all**	**all**	**202**	**35**	**-1.3**	**2.4**

[1] Duration magnitudes (M_D) are used for events with $M_D < 3.0$, and moment magnitudes (M_W) are used for larger events.

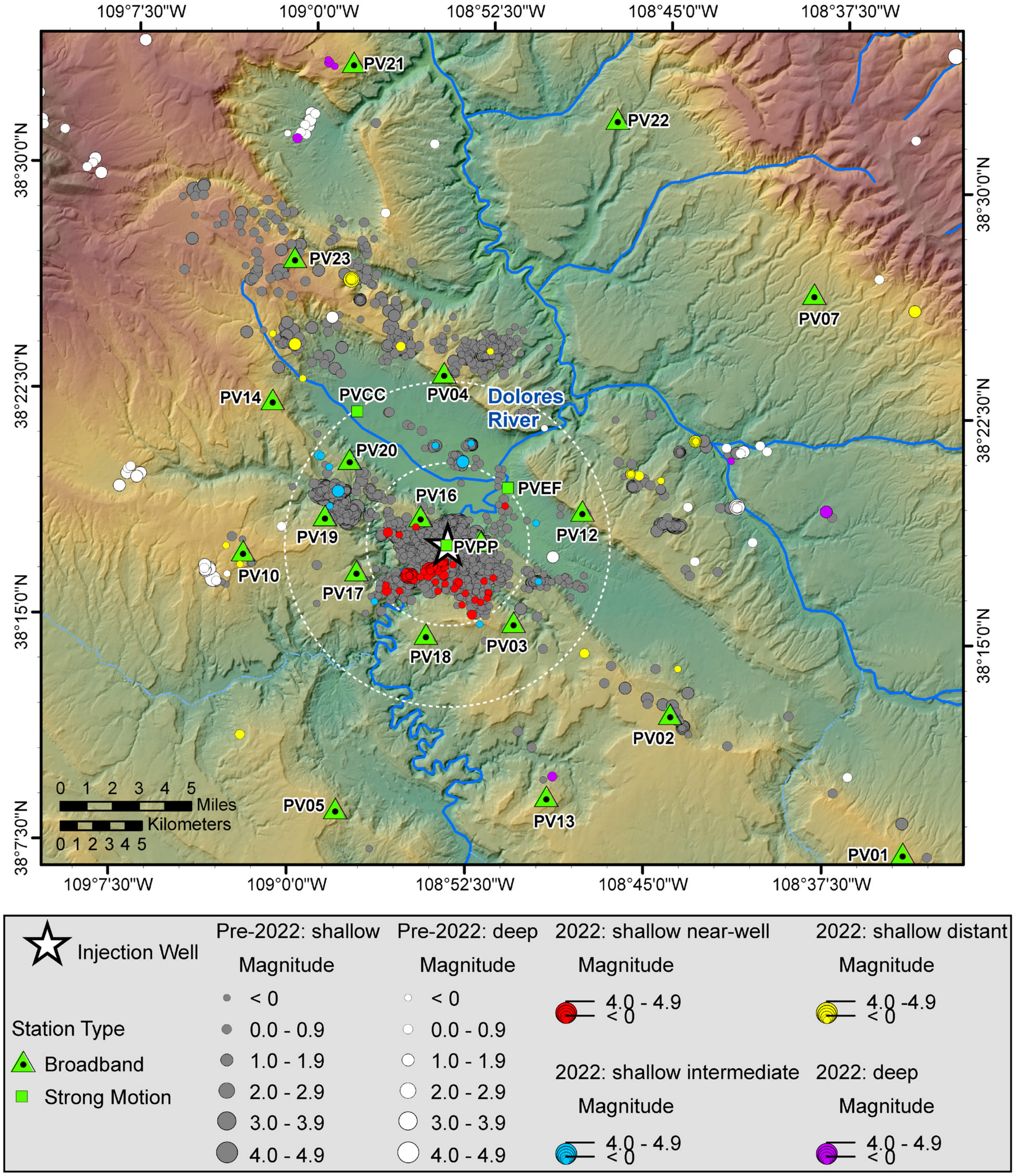


Figure IV-1: Locations of local earthquakes recorded by PVSN during 2022 (colored circles) and previous years (gray and white circles). The events that occurred during 2022 are color-coded using the event location categories described in the text. Events identified as "shallow" have depths ≤ 10 km (relative to the ground surface elevation at the injection well); those identified as "deep" have depths > 10 km. The white dashed circles represent radial distances of 5 and 10 km from the injection well.

No local earthquakes with duration magnitude (M_D) ≥ 2.5 occurred during 2022. This magnitude threshold is significant because it is the approximate minimum magnitude for ground shaking to be felt in the Paradox Valley area. This is the first calendar year since 2016 when no such local earthquakes were recorded.

The local earthquakes recorded by PVSN during 2022 are plotted as a function of date, earthquake magnitude, and location category in Figure IV-2. Earthquake rates were fairly low throughout the year. A small swarm of near-well seismicity occurred in March, with an M_D 2.4 earthquake and several smaller-magnitude events (Figure IV-2, pink squares). Two swarms of low-magnitude, shallow distant seismicity occurred, one in April and one in August (yellow diamonds). Both swarms occurred in seismicity clusters on the far side of Paradox Valley, approximately 12 to 16 km east-northeast of the PVU injection well.

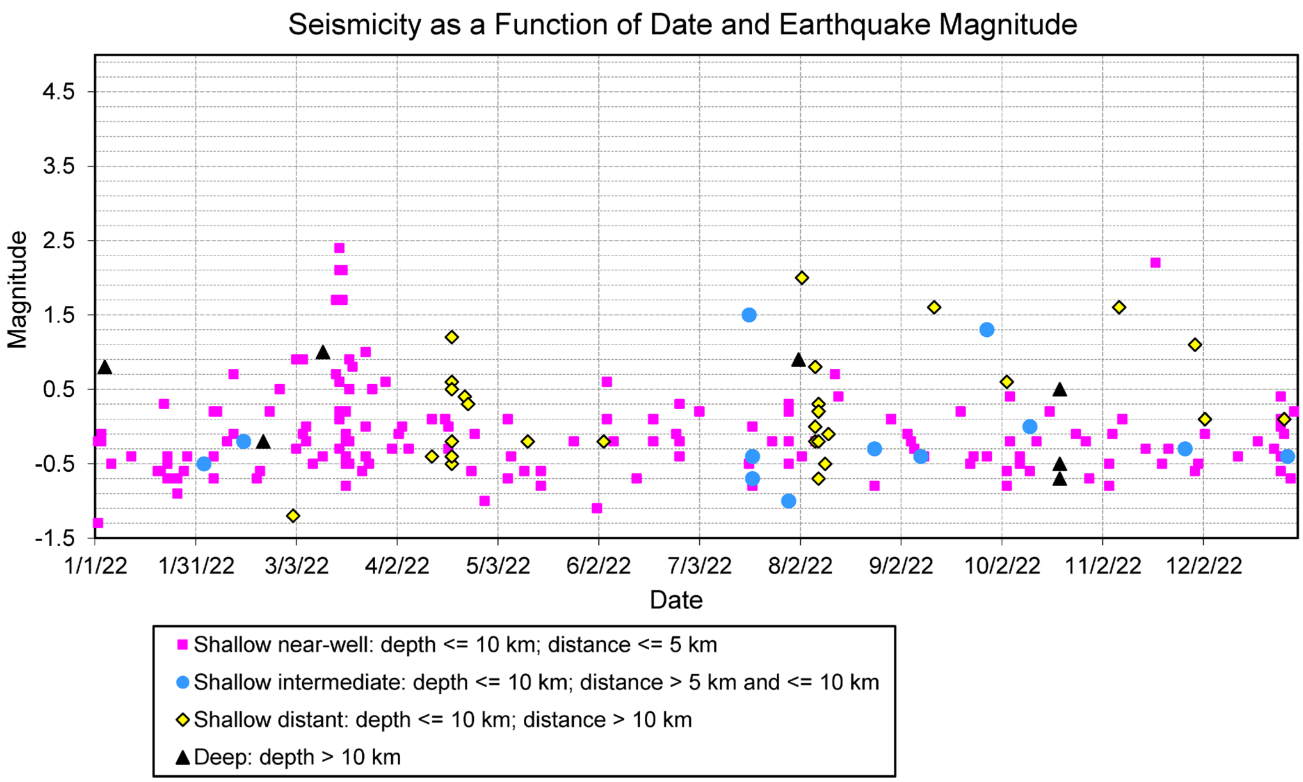


Figure IV-2: Earthquakes recorded by PVSN during 2022 plotted as a function of date, magnitude, and event location category. Duration magnitudes are used for events with M_D < 3.0, and moment magnitudes are used for larger events.

B. Seismicity Near the Injection Well

Hypocenters of the earthquakes that occurred in 2022 within 7 to 9 km of the injection well are compared to those from previous years in the map in Figure IV-3 and in the vertical cross sections in Figure IV-4. In these figures, the earthquakes that occurred in 2022 and those that occurred in previous years are each separated into two categories based on how precise the computed hypocenters are relative to the other events. The best earthquake locations were computed using a relative earthquake location method employing precise arrival time differences between pairs of earthquakes (computed using waveform cross-correlation). The poorer earthquake locations were computed independently using manually determined absolute arrival times because their waveform data were either not of sufficient quantity or quality to include these events in the relative location.

As seen in the map and cross sections, most of the earthquakes induced within ~7-9 km of the injection well during 2022 occurred either near the rupture plane of the March 2019 M_W 4.5 earthquake (white rectangle in Figure IV-3) or in a cluster southwest of the rupture plane (blue circle in Figure IV-3 and Figure IV-4b). Seismicity in this western cluster first began within days of the March 2019 M_W 4.5 earthquake, consistent with aftershock activity expected based on models of Coulomb stress transfer from the main shock fault rupture (Block et al., 2020). However, earthquake rates and magnitudes increased unexpectedly in November 2020. Geomechanical modeling indicates that stress changes associated with depressurization of the reservoir following the shut-in of the injection well in March 2019 may be contributing to the higher-than-expected rates of earthquakes in this area (personal comm., L. Block). The brief near-well seismicity swarm that occurred in March 2022, mentioned earlier (Section IV-A), consisted of earthquakes in this western cluster. The hypocenters of most of these earthquakes are slightly shallower than those of previous earthquakes in this cluster, as illustrated by the cross section in Figure IV-4b. Analyses of relative hypocenters and focal mechanisms suggest that nearly all of the earthquakes in the western cluster occur on a single fault plane; the seismically active portion of the fault plane shifted to slightly shallower depths in 2022.

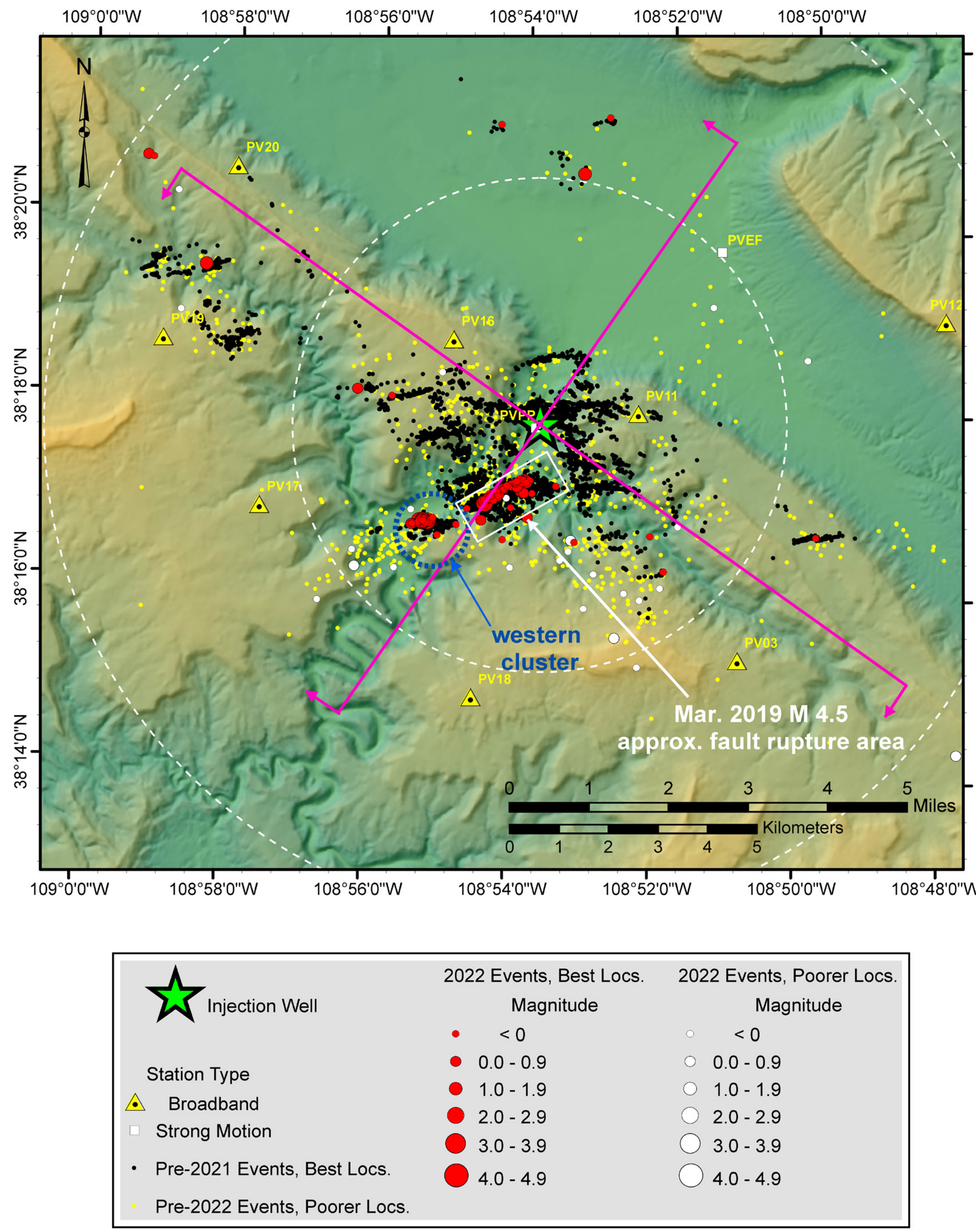
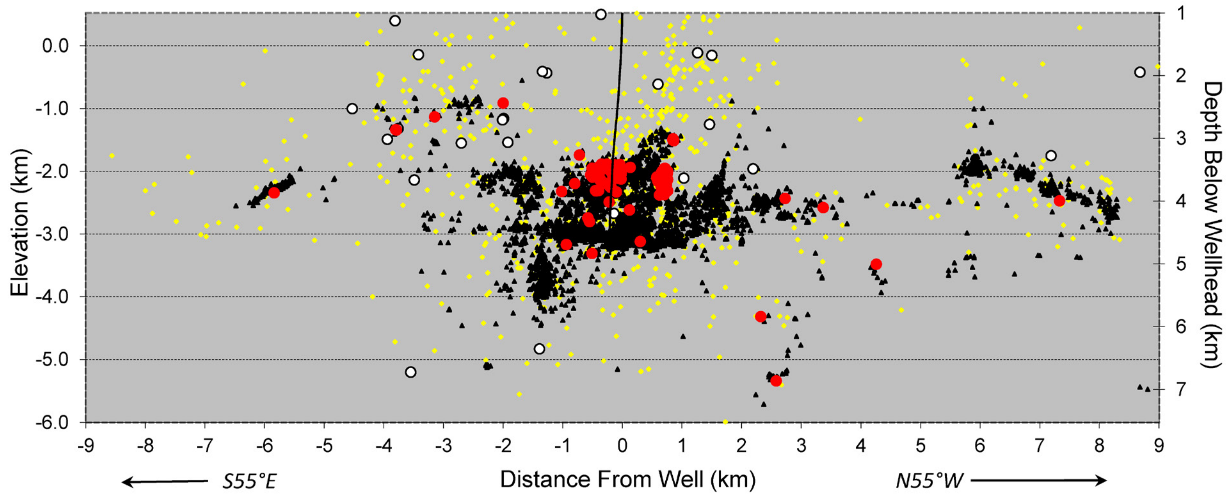


Figure IV-3: Map showing the epicenters of earthquakes (≤ 10 km depth) in the vicinity of the injection well in 2022, compared to the locations of previously induced events. The white dashed circles indicate radial distances of 5 and 10 km from the injection well. The magenta lines indicate the orientations of the cross sections presented Figure IV-4.

(a) Cross section parallel to Paradox Valley, looking to the southwest



(b) Cross section perpendicular to Paradox Valley, looking to the northwest

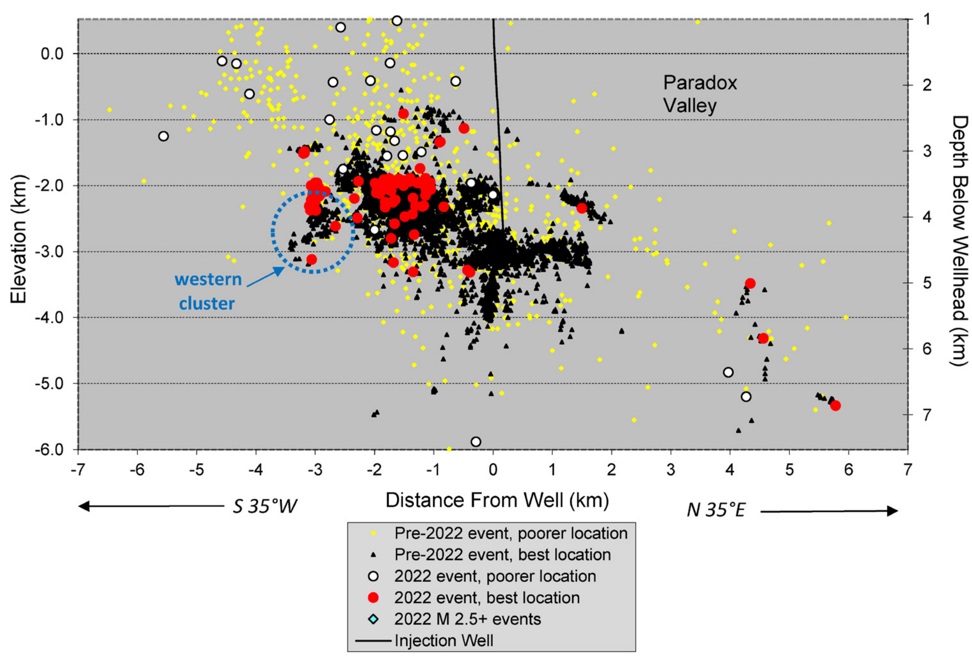


Figure IV-4: Vertical cross sections showing the hypocenters of earthquakes occurring within approximately 7-9 km of the injection well in 2022, compared to the locations of previously induced events: (a) section parallel to Paradox Valley (b) section perpendicular to Paradox Valley. The orientations of the cross sections are indicated by the magenta lines in Figure IV-3.

C. Distant Earthquakes

In 2022, 36 local earthquakes were detected at distances greater than 10 km from the injection well. Of these, 29 earthquakes have depths ≤ 10 km (relative to the ground surface at the injection well). Based on the spatiotemporal evolution of the earthquakes observed since monitoring began in 1985, we interpret these 29 shallow distant earthquakes as likely induced by PVU brine injection. Only one of the seven distant earthquakes with depths > 10 km is currently interpreted as being related to PVU injection (Section IV-A). The discussion below includes the 29 shallow distant earthquakes and the single deep event that is interpreted as being related to PVU injection.

Of the 29 shallow distant earthquakes, eight occurred at or near the northern end of Paradox Valley (Figure IV-1), where seismicity has been detected every year since 2000. For comparison, 20 events occurred in this northern-valley region in 2021, and 30 events occurred here in 2020. Historically, the annual number of northern-valley events has varied widely, ranging from 2 to 725 events per year from 2000 to 2022. The northern-valley earthquakes recorded during 2022 range in magnitude from M_D -0.7 to M_D 2.0. Their depth estimates range from 4.1 km to 8.9 km (relative to the ground surface at the PVU injection well), consistent with depth estimates of previous northern-valley events.

The seismicity in the northern-valley area is expanding to the northwest, beyond the northwestern perimeter of the Paradox Valley Seismic Network (Figure IV-1). Uncertainties in the computed locations and depths of earthquakes increase when they occur outside the perimeter of the seismic monitoring network. Earthquakes are already occurring up to roughly 7 km outside the northwestern perimeter of PVSN. Hence, it will be difficult to monitor the further expansion of the seismicity to the northwest with the current network configuration.

In 2022, 15 earthquakes occurred east of Paradox Valley and south of the Dolores River, at distances of ~12 km to ~17 km from the well (Figure IV-1, yellow circles east of seismic station PV12). These earthquakes include the previously discussed small swarms that occurred in April and August (Section IV-A; Figure IV-1; Figure IV-2). One event with a depth slightly greater than 10 km also occurred in this area during 2022 (Figure IV-1, small purple circle east of seismic station PV12). The magnitudes of the 15 shallow eastern events range from M_D -0.5 to M_D 1.2, and their depth estimates range from 3.5 to 6.5 km (relative to the ground surface at the PVU injection well). The deeper earthquake in this area has a magnitude of M_D -0.2 and depth estimate of 10.4 km. Earthquakes have occurred in this area since 2007. Seismicity rates have generally increased over time, although the number of earthquakes recorded during 2022 (16) is less than the number recorded during the previous year (26). These earthquakes are interpreted as being induced by PVU injection.

Two shallow distant earthquakes occurred southeast of the injection well, at distances of 10.8 and 16.1 km from the well. Seismicity has been observed in this area since 2014 and is interpreted as induced by PVU injection. The earthquakes recorded here in 2022 have magnitudes of M_D 0.1 and M_D -0.5 and depth estimates of 7.4 km and 6.6 km, respectively.

Two shallow distant events occurred ~13 km west of the injection well, near seismic station PV10. These earthquakes have magnitudes of M_D -0.1 and M_D -1.2 and depth estimates of 2.3 km and 2.9 km, respectively. Because of their shallow depth estimates, these events are considered to be potentially induced by PVU injection, possibly triggered by stress changes associated with reservoir deformation.

Of the remaining two shallow distant earthquakes recorded during 2022, one occurred 13.9 km southwest of the injection well (Figure IV-1). This earthquake has a magnitude of M_D 0.6 and a depth estimate of 7.5 km. No other earthquakes have been recorded in this area previously. Any potential relation of this event to PVU injection is unclear. The other event occurred ~32 km east-northeast of the PVU injection well, beyond the perimeter of PVSN (Figure IV-1). This earthquake has a magnitude of M_D 1.6 and a depth estimate of 4.8 km. Because of its large distance from the injection well and other earthquakes induced by PVU injection, we currently consider it unlikely that this event is related to PVU injection.

D. Seismicity Trends

The number of earthquakes interpreted to be due to PVU injection decreased substantially in 2022 compared to 2021, in all distance ranges from the injection well (Table IV-2). The counts in Table IV-2 include all shallow events (depth ≤ 10 km) and the single deep event interpreted as related to PVU injection (see Section IV-A). During 2022, 154 earthquakes were detected within 5 km of the injection well, compared to 273 events in 2021, a decrease of 44%. The number of induced earthquakes at distances of 5 to 10 km from the well decreased 29% from 2021 to 2022, while the number of earthquakes more than 10 km from the well decreased 54% (Table IV-2).

Table IV-2: Number of Induced Earthquakes of All Magnitudes in 2021 and 2022

Distance Range (km)	Number of Events Recorded in 2021	Number of Events Recorded in 2022	Percent Change
0 to 5	273	154	-44%
> 5 to 10	17	12	-29%
> 10	63	29	-54%

Because the ability to detect very small earthquakes can vary over time, depending on both the operating status of the seismic network and background seismic noise levels, more robust estimates of the variation in seismicity rate are determined by comparing the occurrence of earthquakes with magnitude ≥ M_D 0.5 (PVSN's approximate magnitude completeness threshold). These values for the last two years are presented in Table IV-3.

A substantial decrease in seismicity rate is still observed within 5 km of the well (62%). This table indicates a 33% decrease in seismicity rate in the 5-to-10-km distance range, but this statistic is not robust because of the small number of events in the data sets. At distances greater than 10 km from the well, the rate of earthquakes with magnitude ≥ M_D 0.5 decreased by 65% in 2022 compared to 2021.

Table IV-3: Number of Induced Earthquakes With Magnitude ≥ M_D 0.5 in 2021 and 2022

Distance Range (km)	Number of Events Recorded in 2021	Number of Events Recorded in 2022	Percent Change
0 to 5	52	20	-62%
> 5 to 10	3	2	-33%*
> 10	26	9	-65%

*Not reliable because of the small number of earthquakes in the data sets.

The maximum earthquake magnitudes observed in each distance range for the previous two years are compared in Table IV-4. As with other plots presented in this report, duration magnitudes are reported for M_D < 3.0, and moment magnitudes are used for larger events (because the duration magnitude scale saturates above ~M_D 3.0). In the near-well area, the maximum earthquake magnitude decreased slightly from M_D 2.6 in 2021 to M_D 2.4 in 2022. The maximum magnitude also decreased slightly for earthquakes in the intermediate distance range (5 to 10 km from the injection well), from M_D 1.7 in 2021 to M_D 1.5 in 2022. In contrast, the maximum magnitude in the largest distance range (>10 km from the well) increased from M_D 1.7 in 2021 to M_D 2.0 in 2022.

Table IV-4: Maximum Earthquake Magnitudes in 2021 and 2022

Distance Range (km)	Mmax in 2021	Mmax in 2022
0 to 5	M_D 2.6	M_D 2.4
> 5 to 10	M_D 1.7	M_D 1.5
> 10	M_D 1.7	M_D 2.0

Longer-term trends of earthquake rates and magnitudes are presented in three plots described below. Events with M_D ≥ 0.5 and depth ≤ 12 km are included in these plots. First, the bubble plots in Figure IV-5 show the historical occurrence of seismicity as a function of date and earthquake magnitude during long-term injection at PVU (since 1996). The area of each circle in these plots is scaled by the number of earthquakes in a given quarter-year and magnitude range. Individual bubble plots are included for earthquakes occurring within 5 km of the injection well, between 5 and 10 km from the well, and more than 10 km from the well. The daily average injection rates are included in Figure IV-5 for reference. In order to better observe the trends in recent years, similar plots that only include data from 2012 to 2022 are presented in Figure IV-6. Lastly, we show the annual seismicity rates for the last 15 years, for the different distances from the well, in Figure IV-7.

These plots show that the seismicity rates for the near-well area (within 5 km of the well) remained somewhat high in the first quarter of 2022 but were low compared to historical trends for the remainder of the year (Figure IV-5b and Figure IV-6b). The maximum magnitude of near-well events was unusually low ($\leq M_D$ 1.0) during the second and third quarters of 2022. The annual rate of near-well seismicity has decreased every year since 2019 (when the M_W 4.5 near-well induced earthquake occurred). In 2022, the near-well seismicity rate was comparable to pre-2019 rates (Figure IV-7a).

The seismicity rates at distances of 5 to 10 km from the injection well were low in 2022 compared to historical trends (Figure IV-5c and Figure IV-6c). Annual seismicity rates in this distance range have been relatively low for the last four years, since the injection well was shut down in early 2019 (Figure IV-7b). The rates were also low in 2014-2015, following a 3-month injection well shut-in in early to mid-2013 (Figure IV-7b). This pattern suggests that earthquakes at these distances may be more sensitive to injection operations than a simple pore pressure diffusion model would suggest.

The rate of distant M 0.5+ events, those occurring more than 10 km from the injection well, have historically been highly variable (Figure IV-5d). The annual rate observed in 2022 was low compared to the last several years (Figure IV-7c).

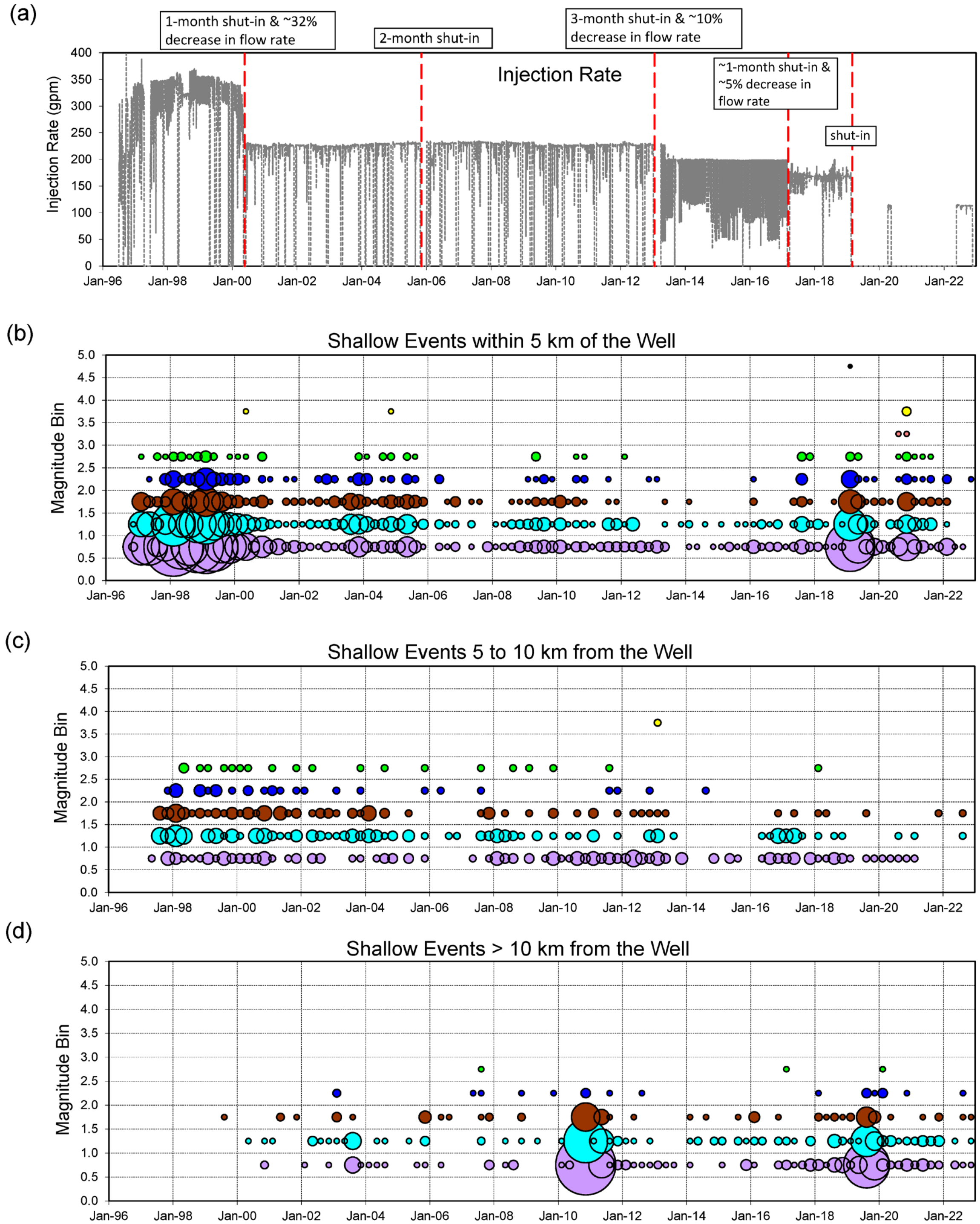


Figure IV-5: Injection flow rates (a) and occurrence of seismicity with $M_D \geq 0.5$ and depth ≤ 12 km as a function of date and magnitude: (b) within 5 km of the injection well, (c) at distances of 5 to 10 km from the well, and (d) more than 10 km from the well. In the seismicity plots, the area of each circle is scaled by the number of earthquakes in a given quarter-year and magnitude range; each plot is scaled independently. Duration magnitudes are used for events with $M_D < 3.0$, and moment magnitudes are used for larger events.

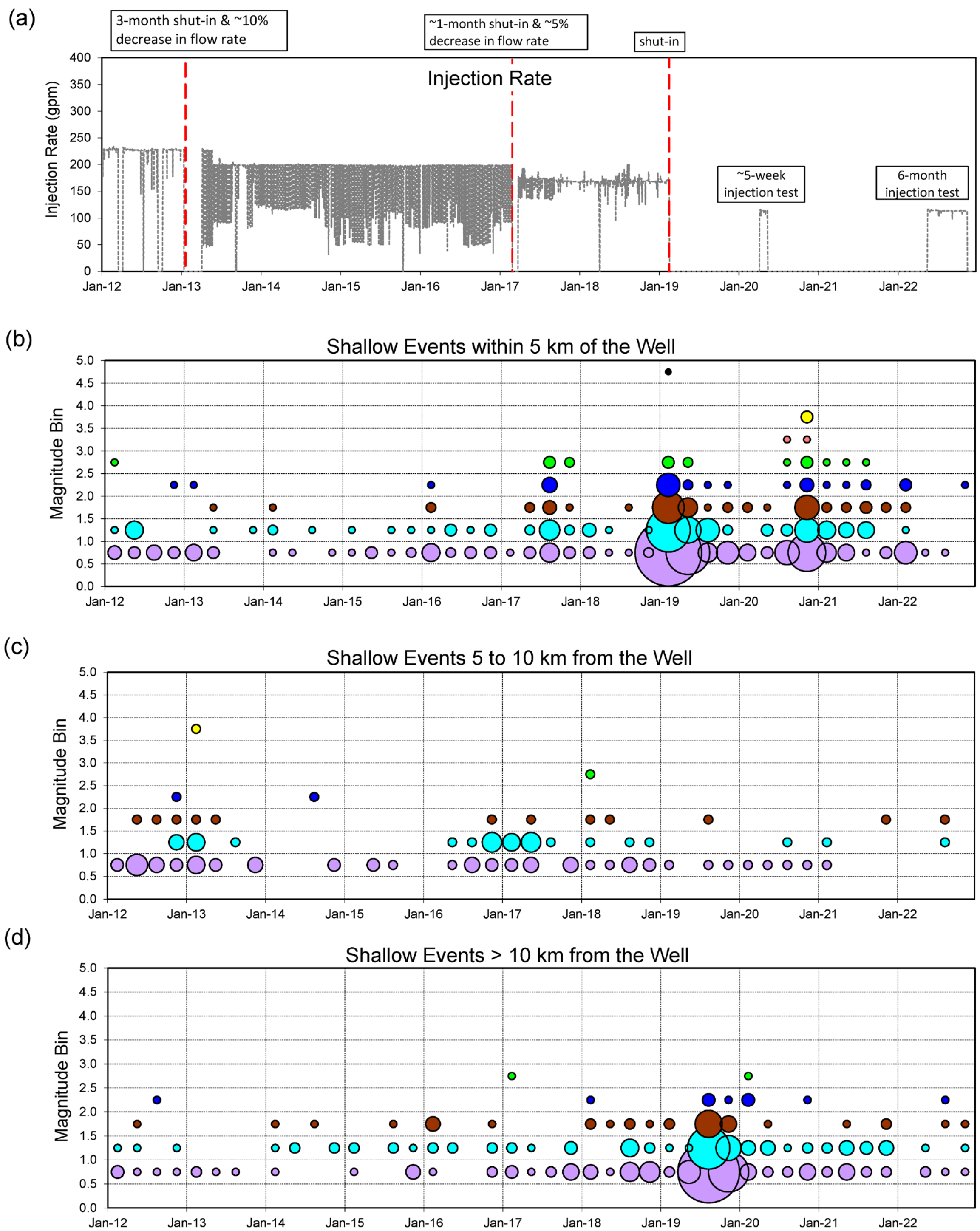


Figure IV-6: Same as Figure IV-5, but only showing data from 2012-2022.

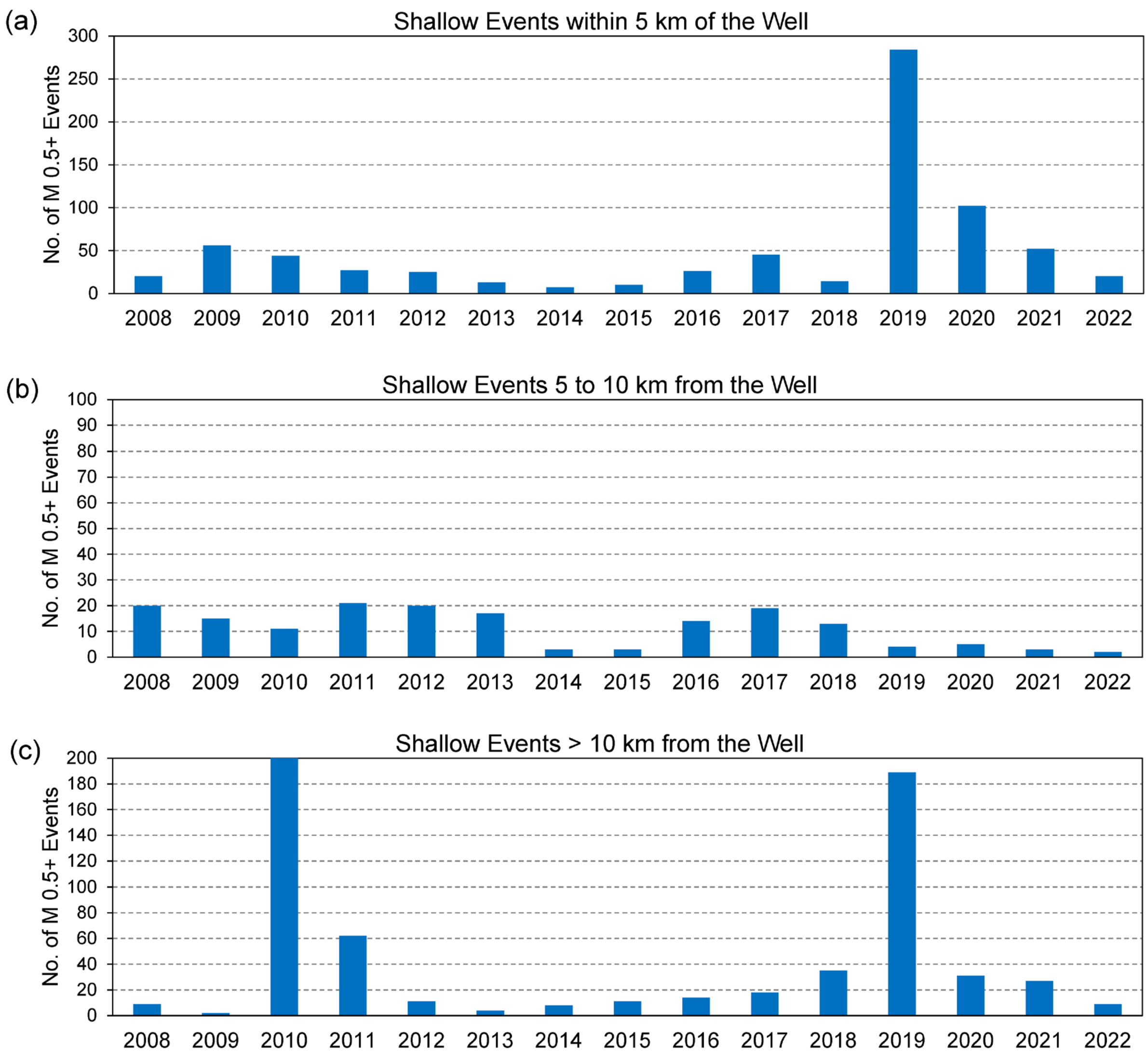


Figure IV-7: Annual numbers of earthquakes with $M_D \geq 0.5$ and depth ≤ 12 km: (a) within 5 km of the injection well, (b) 5 to 10 km from the well, and (c) more than 10 km from the well. Data for the last 15 years are shown.

V. Other Activities

A. Probabilistic Seismic Hazard Analysis

In 2022, Reclamation completed a probabilistic seismic hazard analysis for seismicity induced by the Paradox Valley Unit. The details of that study are documented in a separate report (Wood, 2022). The Executive Summary from that report is included below:

The occurrence of an M_W 4.5 induced earthquake at PVU in March 2019 indicates that induced earthquakes at PVU may reach the magnitude threshold for causing damage in surrounding areas if injection operations continue as before. The magnitude threshold for damage is generally assumed to be in the range of M_W = 4.7-5.0 *for seismic hazard analyses of engineered structures. Even if injection is halted permanently, induced earthquakes may continue for many years as the pore pressure front created by 25 years of brine disposal continues to diffuse away from the well and pressurize additional subsurface volumes.*

In order to assess the short-term risks from future induced earthquakes, a seismic hazard analysis has been conducted to evaluate the areas surrounding PVU that are most likely to be subject to strong shaking from induced earthquakes over the next few years, assuming that the past 25-year rate of seismicity remains roughly constant. Although the seismicity response to injection has been complex both spatially and temporally, simple models indicate that those areas most likely to be significantly affected are within about 45 km of the injection well. These are the areas that should receive the greatest focus during any subsequent seismic risk analyses.

The methods used for this study were developed from those used for analyzing natural seismicity, which tends to occur uniformly over time. In contrast, seismicity rates at PVU have been highly variable, and do not exactly follow the models assumed for natural earthquakes. Furthermore, models which predict seismicity rates from injection parameters such as cumulative volume or downhole pressure have considerable uncertainty and have not reproduced the spatial and temporal distribution of seismicity at PVU. Thus, the approach of this study is to use simple models based on the 25-year average rate of induced seismicity observed from 1987-2021 as a baseline to make a short-term estimate of hazard. This approach has been used for short-term hazard estimates for induced seismicity in other areas, such as Oklahoma and Texas.

VI. Conclusions

PVSN recorded 202 local earthquakes during 2022. The spatiotemporal seismicity trends observed since 1985 provide strong evidence that 196 of these events were induced by PVU brine injection. Five of the remaining six earthquakes are interpreted as naturally occurring, while any potential relation of the sixth event to PVU injection is unclear.

No induced earthquakes with magnitude ≥ M_D 2.5 occurred during 2022. This magnitude threshold is significant because it is the approximate minimum magnitude for ground shaking to be felt in the Paradox Valley area. This is the first calendar year since 2016 when no such earthquakes were recorded.

Near-well seismicity rates (of M_D 0.5+ events) decreased ~62% in 2022 compared to 2021, as the rate of aftershocks of the March 2019 M_W 4.5 earthquake continued to decline. The 2022 annual near-well seismicity rate was comparable to annual near-well rates preceding the 2019 M_W 4.5 earthquake.

The seismicity rate at distances of 5 to 10 km from the PVU injection well decreased slightly in 2022 compared to the previous year, although quantitative statistics are not robust because of the small numbers of events in the data sets. At distances > 10 km from the well, the rate of M_D 0.5+ events decreased ~65% compared to the previous year and was low compared to longer-term historical trends. Induced seismicity is occurring several km outside the perimeter of PVSN, decreasing the ability of the seismic network to detect and provide accurate locations for all of the induced earthquakes.

PVSN performed well during 2022, with an annual network uptime of 100%. Uptimes of individual seismic stations ranged from 66% to 100%, with 21 of the 23 stations having uptimes ≥ 98%**.**

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Appendix A

2022 Site Visit Reports

Paradox Valley Seismic Network
Site Visit Report

Site Visit Number: PVSN-2022-01
Prepared by: Justin Schwarzer
Departure Date: May 4, 2022
Return Date: May 8, 2022
Personnel: Justin Schwarzer, Jong Kang

Primary Purpose: Main priorities were to restore station PV18, troubleshoot the strong motion sites, and perform general preventive maintenance at other stations.

Details:
At station PV18, the DM24-BOB had failed and was replaced. The system is now fully functional.

Testing was performed at strong motion sites PVPP and PVCC to help understand the intermittent noise issue seen at both stations. Results of tests at both sites appear to be inconclusive on the cause of the issue.

Routine testing of radio and power systems was performed at stations PV02, PV03, PV10, PV11, PV12, PV13, PV17 and PV18. In addition, new batteries were installed at station PV11. Three gallons of water were added to the PV02 chem-rod.

The PV13 radio cable had substantial bear damage. The cable was replaced, and hog wire was placed around the lower tower. Testing after the installation of the new cable showed improvement to the radio statistics. The wire from the positive-side solar panel to the Prostar solar charge controller was completely disconnected and held in place by friction. The wire was completely re-seated during the site visit.

A seismometer vault inspection was performed at station PV10. The vault was found to be dry and clean, but the glass plate was shattered.

It was noted that grounding work has not been completed at stations PV03, PV10, and PV18. It was also noted that PV17’s radio cable needs to be replaced, as it has bear damage. The cable was sealed with tape on this trip; a full replacement needs to be scheduled.

Summary of Work by Site:

Site	Checked Power System	Replaced Batteries	Performed Antenna Test	Performed Wattmeter Test	Inspected Vault	Comments
PV02	X		X			
PV03	X		X			
PV10	X		X		X	Opened vault, glass plate was shattered
PV11	X	X	X			Replaced Batteries
PV12	X		X			
PV13	X		X			Replaced radio cable and added hog wire
PV17	X		X			Radio cable needs to be replaced
PV18	X		X			Replaced DM24-BOB

Abbreviations:

AP-1 – access point #1 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from individual stations PV01, PV07, and PV15

AP-2 – access point #2 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from radio repeater station PV02

AP-3 – access point #3 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from radio repeater stations PV04 and PV12

Chem rod – chemical ground rod that is part of the lightning protection grounding system at station PV02

DM24-BOB - seismic station electronics break-out-box located in enclosure; conditions power supply for the DM24 seismometer digitizer

GPS – refers to antenna that receives Global Positioning System satellite data to provide station timing

GPS-BOB - seismic station electronics break-out-box located in enclosure; serves as junction for dirty and clean power supplies and data communications

LVD - low-voltage disconnect

SPM – station power monitor

WAGO – refers to special tool needed for engaging (or disengaging) some electronics connections within station enclosure; manufactured by WAGO Corporation

Paradox Valley Seismic Network
Site Visit Report

Site Visit Number: PVSN-2022-02
Prepared by: Justin Schwarzer
Departure Date: September 20, 2022
Return Date: September 28, 2022
Personnel: Justin Schwarzer, David Heeszel

Primary Purpose: Perform general preventive maintenance at PVSN stations.

Details:

Routine testing of radio antenna and power systems was performed at stations PV01, PV02, PV04, PV05, PV07, PV12, PV14, PV15, PV17, PV19, PV20, PV21, PV22, PV23, PVCC, PVEP, and PVPP.

New batteries were installed at PV01, PV07, PV21, PV22, and PV23.

Seismometer vaults were opened and inspected at PV19, PV20, and PV23. No damage was found during these inspections.

The PV17 radio cable had substantial bear damage and required replacement. Antenna testing indicated a significant improvement in functionality after the cable was replaced.

Animal bite damage was found at station PV05 on the antenna cable. The inner metal casing was not damaged, and no abnormalities were found during testing. The cable was not replaced.

The GPS cable tubing at PV15 was found to be damaged by an animal. The GPS cable itself had not received any damage. The tubing was sealed with tape; the tubing should be replaced during the next site visit. The internal connections on the GPS-BOB were inspected for pulling damage; the ribbon cable was found to be pinched and cut. The ribbon was replaced.

Hog wire for animal protection was installed at stations PV15, PV17, and PV23.

Open-circuit unloaded solar panel testing showed unsatisfactory results (< 20V) in full sun at PV01, PV12, PV19, PV20, PV22, and PV23. All panels showed signs of discoloration.

Weather stripping was installed behind the entry door of the station enclosure at PVCC. The site has been flooding during rain through gaps at the top of the door.

The power system at PVPP was reconfigured to utilize the BC-15 system without the need for WAGO terminal blocks.

Antenna testing at Hopkins Field was unsuccessful. Radio signals from an unidentified source caused interference that prevented accurate measurements. Two new switches were brought to the shelter for storage until installation. A new external hard drive was installed for data backup, and the older external hard drive was brought back to Denver to retrieve archived data.

Road damage is significant on the paths to PV19 and PV20. Options for road repairs should be explored.

Summary of Work by Site:

Site	Checked Power System	Replaced Batteries	Performed Antenna Test	Performed Wattmeter Test	Inspected Vault	Comments
PV01	X	X	X			Open-circuit solar panel voltage low
PV02	X		X			
PV04	X		X			
PV05	X		X			
PV07	X	X	X			
PV12	X		X			Open-circuit solar panel voltage low
PV14	X		X			
PV15	X		X			GPS cable tubing damaged – should be replaced on next trip. GPS-BOB ribbon cable was replaced.
PV17	X		X			Antenna cable replaced
PV19	X		X		X	Open-circuit solar panel voltage low; significant road damage
PV20	X		X		X	Open-circuit solar panel voltage low; significant road damage
PV21	X	X	X			
PV22	X	X	X			Open-circuit solar panel voltage low
PV23	X	X	X		X	Open-circuit solar panel voltage low
PVPP	X		X			
PVEF	X		X			
PVCC	X		X			Weather stripping installed
Hopkins			*			*Antenna test was unsuccessful due to radio interference from an unidentified source.

Abbreviations:

AP-1 – access point #1 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from individual stations PV01, PV07, and PV15

AP-2 – access point #2 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from radio repeater station PV02

AP-3 – access point #3 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from radio repeater stations PV04 and PV12

Chem rod – chemical ground rod that is part of the lightning protection grounding system at station PV02

DM24-BOB - seismic station electronics break-out-box located in enclosure; conditions power supply for the DM24 seismometer digitizer

GPS – refers to antenna that receives Global Positioning System satellite data to provide station timing

GPS-BOB - seismic station electronics break-out-box located in enclosure; serves as junction for dirty and clean power supplies and data communications

LVD - low-voltage disconnect

SPM – station power monitor

WAGO – refers to special tool needed for engaging (or disengaging) some electronics connections within station enclosure; manufactured by WAGO Corporation

Appendix B

PVSN 2022 Local Earthquake Catalog

Table B-1: Local Earthquakes Recorded by PVSN During 2022

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	M_D[4]	M_W[4]	Horizontal Distance from Injection Well (km)
1/2/22	18:30:25	38.2700	-108.9008	-0.4300	2.0	-0.2		3.0
1/2/22	18:30:39	38.2743	-108.8960	-0.4100	1.9	-1.3		2.5
1/3/22	0:49:34	38.2863	-108.8989	-2.1220	3.6	-0.2	1.1	1.2
1/3/22	9:00:38	38.2862	-108.8990	-2.1480	3.7	-0.1		1.2
1/4/22	20:31:46	38.1700	-108.8157	-28.9900	30.5	0.8		15.7
1/6/22	13:54:46	38.2861	-108.8985	-1.9370	3.5	-0.5		1.2
1/12/22	4:27:36	38.2779	-108.9220	-2.1810	3.7	-0.4	0.9	3.1
1/20/22	15:04:32	38.3052	-108.9180	-1.9600	3.5	-0.6		2.2
1/21/22	20:27:15	38.2836	-108.9044	-1.9240	3.4	-0.6		1.7
1/22/22	3:31:17	38.2859	-108.8991	-1.9900	3.5	0.3	1.2	1.2
1/23/22	3:07:28	38.3187	-108.8558	-4.8300	6.4	-0.4	0.9	4.2
1/23/22	19:09:42	38.2848	-108.9018	-1.9190	3.4	-0.5		1.4
1/23/22	19:11:19	38.2848	-108.9017	-1.8860	3.4	-0.7		1.4
1/26/22	12:31:19	38.2785	-108.8623	-2.1400	3.7	-0.9		3.5
1/26/22	12:31:28	38.2766	-108.8687	-1.1320	2.7	-0.7		3.2
1/28/22	8:47:52	38.2775	-108.9238	-1.4820	3.0	-0.6		3.3
1/29/22	12:54:14	38.2860	-108.8994	-1.9750	3.5	-0.4		1.2
2/3/22	6:57:56	38.3150	-108.9790	-1.7500	3.3	-0.5		7.6
2/6/22	1:03:18	38.2774	-108.9240	-1.5130	3.0	0.2	0.8	3.3
2/6/22	12:24:02	38.2672	-108.8660	-1.4900	3.0	-0.7		4.1
2/6/22	23:35:48	38.2703	-108.8653	-1.3380	2.9	-0.4		3.9
2/7/22	0:53:48	38.2774	-108.9240	-1.4940	3.0	0.2	0.9	3.3
2/10/22	7:49:57	38.2774	-108.9241	-1.5080	3.0	-0.2	0.7	3.3
2/12/22	2:26:55	38.2775	-108.9239	-1.5050	3.0	-0.1	0.9	3.3
2/12/22	22:35:22	38.2850	-108.9010	-2.1880	3.7	0.7	1.2	1.4
2/15/22	1:49:18	38.2856	-108.8977	-2.0950	3.6	-0.2	0.8	1.2
2/15/22	22:01:22	38.2774	-108.8304	-2.3430	3.9	-0.2	1.1	6.0
2/19/22	20:50:17	38.2827	-108.9022	0.5000	1.0	-0.7		1.7
2/20/22	6:39:23	38.2778	-108.9208	-2.2440	3.8	-0.6		3.1
2/21/22	1:29:47	38.3479	-108.6980	-8.9000	10.4	-0.2		18.1
2/23/22	23:13:10	38.2825	-108.9060	-2.3280	3.9	0.2	1.0	1.8
2/26/22	7:24:58	38.2855	-108.8986	-2.3150	3.8	0.5	1.1	1.3
3/2/22	21:38:29	38.2910	-109.0510	-1.3400	2.9	-1.2		13.7
3/3/22	3:03:08	38.2774	-108.9218	-2.3730	3.9	0.9	1.2	3.2
3/3/22	15:46:10	38.2703	-108.8654	-1.3420	2.9	-0.3		3.9
3/5/22	8:46:59	38.2717	-108.8893	-1.1600	2.7	-0.1		2.8
3/5/22	15:58:00	38.2733	-108.8875	-1.1800	2.7	-0.1		2.7
3/5/22	19:30:16	38.2753	-108.8870	-1.5400	3.1	0.9	1.5	2.5
3/6/22	5:41:21	38.2777	-108.9211	-2.2780	3.8	-0.2	0.9	3.1
3/6/22	7:35:22	38.2777	-108.9212	-2.2840	3.8	0.0	0.8	3.1
3/8/22	20:15:51	38.2821	-108.9051	-2.2510	3.8	-0.5		1.8
3/11/22	3:30:08	38.2861	-108.8971	-1.9540	3.5	-0.4	0.9	1.2
3/11/22	12:24:48	38.3217	-108.6298	-14.3700	15.9	1.0	1.1	23.4
3/15/22	22:13:16	38.2779	-108.9215	-2.1990	3.7	0.7	1.8	3.1
3/15/22	22:13:28	38.2779	-108.9211	-2.1580	3.7	1.7	2.3	3.1
3/16/22	0:37:47	38.2780	-108.9214	-2.1060	3.6	2.1	2.4	3.1
3/16/22	0:54:41	38.2781	-108.9218	-2.1020	3.6	0.1	1.1	3.1
3/16/22	1:05:48	38.2781	-108.9210	-2.0280	3.6	0.6	1.3	3.1

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	M_D[4]	M_W[4]	Horizontal Distance from Injection Well (km)
3/16/22	14:59:53	38.2779	-108.9217	-2.1840	3.7	0.2		3.1
3/16/22	20:41:48	38.2780	-108.9203	-2.1310	3.7	2.4	2.5	3.0
3/16/22	20:47:58	38.2781	-108.9212	-2.0260	3.6	-0.3	0.8	3.1
3/17/22	0:29:56	38.2780	-108.9221	-2.1320	3.7	2.1	2.0	3.1
3/17/22	17:02:54	38.2781	-108.9216	-2.0230	3.5	1.7	2.2	3.1
3/18/22	2:58:23	38.2800	-108.9242	-2.1100	3.6	-0.4		3.1
3/18/22	4:51:05	38.2781	-108.9220	-2.0050	3.5	-0.4	0.7	3.1
3/18/22	5:47:33	38.2781	-108.9213	-2.0040	3.5	-0.8		3.1
3/18/22	10:30:31	38.2781	-108.9219	-2.0360	3.6	0.2	0.7	3.1
3/18/22	11:49:32	38.2781	-108.9219	-2.0370	3.6	-0.5	0.5	3.1
3/18/22	16:30:32	38.2780	-108.9211	-2.1160	3.6	-0.5	0.7	3.1
3/18/22	18:51:15	38.2781	-108.9194	-2.1050	3.6	-0.2	0.7	3.0
3/18/22	23:34:45	38.2782	-108.9208	-2.0110	3.5	-0.1	0.9	3.0
3/19/22	3:28:26	38.2780	-108.9220	-2.0420	3.6	-0.5		3.1
3/19/22	16:00:11	38.2778	-108.9220	-2.2030	3.7	-0.2	0.8	3.1
3/19/22	16:00:35	38.2778	-108.9219	-2.2190	3.7	0.5	1.2	3.1
3/19/22	16:22:21	38.2782	-108.9204	-2.0290	3.6	0.9	1.3	3.0
3/20/22	22:18:32	38.2779	-108.9200	-2.1620	3.7	0.8	1.5	3.0
3/23/22	13:01:30	38.3006	-108.9295	-2.4340	4.0	-0.6		3.1
3/24/22	6:53:59	38.2859	-108.8982	-2.0370	3.6	1.0	1.3	1.2
3/24/22	8:03:45	38.2859	-108.8983	-2.0460	3.6	0.0	1.0	1.2
3/24/22	19:31:34	38.2781	-108.9219	-2.0140	3.5	-0.4		3.1
3/25/22	11:20:06	38.2778	-108.9223	-2.0000	3.5	-0.5	0.6	3.2
3/26/22	10:29:49	38.3017	-108.9375	-2.5790	4.1	0.5	1.1	3.8
3/30/22	7:23:34	38.2782	-108.9207	-1.9970	3.5	0.6	1.1	3.0
4/1/22	12:12:38	38.2781	-108.9198	-2.1440	3.7	-0.3		3.0
4/3/22	15:13:53	38.2777	-108.9209	-2.2620	3.8	-0.1	0.9	3.1
4/4/22	23:03:45	38.2837	-108.8983	-2.7440	4.3	0.0	1.0	1.5
4/6/22	6:30:45	38.2786	-108.9190	-2.0900	3.6	-0.3		2.9
4/13/22	10:45:01	38.2777	-108.9221	-2.2210	3.7	0.1	0.8	3.2
4/13/22	14:37:04	38.3582	-108.7233	-3.9260	5.5	-0.4		16.5
4/17/22	10:31:04	38.2783	-108.9211	-1.9570	3.5	0.1	1.0	3.1
4/18/22	0:06:14	38.2783	-108.9211	-1.9720	3.5	-0.3	0.8	3.1
4/18/22	13:29:44	38.2847	-108.8998	-2.3080	3.8	0.0		1.4
4/19/22	10:43:03	38.3581	-108.7236	-3.8700	5.4	0.6	1.4	16.5
4/19/22	10:43:12	38.3582	-108.7234	-3.8740	5.4	-0.5		16.5
4/19/22	10:43:50	38.3582	-108.7236	-3.8650	5.4	-0.2		16.5
4/19/22	10:45:48	38.3582	-108.7236	-3.8720	5.4	-0.4		16.5
4/19/22	10:47:05	38.3582	-108.7236	-3.8600	5.4	0.5		16.5
4/19/22	10:54:24	38.3582	-108.7236	-3.8700	5.4	1.2	1.2	16.5
4/23/22	0:39:25	38.3581	-108.7234	-3.8700	5.4	0.4	1.1	16.5
4/24/22	18:42:54	38.4410	-108.9700	-4.0450	5.6	0.3	1.0	17.3
4/25/22	20:34:17	38.2781	-108.9215	-1.9560	3.5	-0.6	0.5	3.1
4/26/22	8:42:38	38.2777	-108.9211	-2.2750	3.8	-0.1	0.8	3.1
4/29/22	23:43:25	38.2648	-108.8707	-1.3200	2.8	-1.0		4.1
5/6/22	15:24:39	38.2856	-108.8976	-2.0940	3.6	0.1	0.9	1.2
5/6/22	15:34:02	38.2856	-108.8977	-2.0880	3.6	-0.7	0.8	1.2
5/7/22	6:32:17	38.2851	-108.8909	-2.3210	3.8	-0.4		1.3
5/11/22	13:28:52	38.2843	-108.9029	-1.9270	3.5	-0.6		1.5

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	M_D[4]	M_W[4]	Horizontal Distance from Injection Well (km)
5/12/22	10:52:32	38.4092	-109.0240	-7.4000	8.9	-0.2		16.8
5/16/22	6:04:10	38.2837	-108.9043	-1.9470	3.5	-0.8	0.5	1.6
5/16/22	9:45:07	38.2842	-108.9030	-1.9290	3.5	-0.6		1.5
5/26/22	8:48:08	38.2860	-108.8969	-2.0580	3.6	-0.2	0.7	1.2
6/2/22	14:35:52	38.2810	-108.9068	-2.6700	4.2	-1.1		2.0
6/4/22	6:48:50	38.3850	-109.0015	-2.5400	4.1	-0.2	0.8	13.5
6/5/22	12:37:34	38.2776	-108.9218	-2.3260	3.9	0.6	1.1	3.2
6/5/22	12:59:26	38.2775	-108.9220	-2.3380	3.9	0.1	0.7	3.2
6/7/22	13:46:00	38.2776	-108.9225	-2.3120	3.8	-0.2	0.7	3.2
6/14/22	20:48:44	38.2849	-108.9021	-1.9400	3.5	-0.7	0.5	1.4
6/19/22	5:21:58	38.2843	-108.9030	-2.0000	3.5	-0.2		1.5
6/19/22	5:57:14	38.2843	-108.9030	-1.9970	3.5	0.1	0.9	1.5
6/26/22	12:35:41	38.2841	-108.9031	-1.9220	3.4	-0.1		1.5
6/27/22	5:44:23	38.2854	-108.9002	-1.9570	3.5	-0.4		1.3
6/27/22	5:44:40	38.2853	-108.9002	-1.9590	3.5	-0.2	0.8	1.3
6/27/22	11:09:41	38.2855	-108.8985	-2.3060	3.8	-0.2		1.3
6/27/22	22:06:23	38.2842	-108.9031	-1.9390	3.5	0.3	0.8	1.5
7/3/22	10:27:07	38.2837	-108.9042	-1.9620	3.5	0.2	0.9	1.6
7/18/22	5:31:13	38.2830	-108.9061	-1.9120	3.4	-0.5		1.8
7/18/22	6:44:27	38.3422	-108.8868	-4.3150	5.8	1.5	1.4	5.1
7/19/22	7:02:39	38.3426	-108.9865	-3.3160	4.8	-0.4	0.4	9.5
7/19/22	7:03:38	38.3367	-108.9805	-0.4200	1.9	-0.7		8.7
7/19/22	17:23:15	38.2833	-108.9051	-1.9410	3.5	0.0	1.4	1.7
7/19/22	18:22:51	38.2830	-108.9058	-1.9800	3.5	-0.8		1.8
7/25/22	10:04:00	38.2723	-108.9375	-0.1500	1.7	-0.2	0.5	4.6
7/30/22	10:21:11	38.2819	-108.9076	-2.0440	3.6	0.3	0.8	2.0
7/30/22	10:29:51	38.2820	-108.9075	-2.0380	3.6	-0.2	0.7	2.0
7/30/22	15:18:27	38.2823	-108.9073	-2.1220	3.6	-0.5		1.9
7/30/22	22:00:14	38.2578	-108.8762	0.4000	1.1	0.2	0.9	4.6
7/30/22	22:01:16	38.2527	-108.8707	-1.0000	2.5	-1.0		5.3
8/2/22	5:14:27	38.5180	-109.0117	-12.3800	13.9	0.9	1.4	26.6
8/3/22	8:49:59	38.4409	-108.9699	-4.0450	5.6	2.0	1.6	17.3
8/3/22	10:52:47	38.2819	-108.9076	-2.0350	3.6	-0.4		2.0
8/7/22	4:47:21	38.3357	-108.7468	-2.0100	3.5	-0.2		13.7
8/7/22	7:19:09	38.3382	-108.7623	-4.9500	6.5	0.8	1.2	12.5
8/7/22	9:34:42	38.2840	-108.9041	-1.8970	3.4	-0.2		1.6
8/7/22	13:05:55	38.3390	-108.7685	-4.9890	6.5	-0.2		12.0
8/7/22	13:31:11	38.3389	-108.7684	-4.9430	6.5	0.0	0.8	12.0
8/8/22	4:20:02	38.3390	-108.7687	-4.9480	6.5	0.3	1.2	12.0
8/8/22	4:21:13	38.3390	-108.7686	-4.9460	6.5	0.2	1.2	12.0
8/8/22	5:36:21	38.4040	-108.8703	-4.4450	6.0	-0.7	0.4	12.1
8/8/22	19:06:45	38.3389	-108.7682	-4.9590	6.5	-0.2		12.0
8/10/22	3:52:47	38.2318	-108.7303	-5.0500	6.6	-0.5		16.1
8/11/22	16:07:46	38.2808	-109.0407	-0.7600	2.3	-0.1	0.7	12.9
8/13/22	15:21:40	38.2839	-108.8990	-3.3080	4.8	0.7	1.1	1.4
8/14/22	9:07:23	38.2833	-108.9039	-2.2160	3.7	0.4		1.7
8/25/22	2:23:00	38.3097	-108.8337	-5.2000	6.7	-0.3	1.2	5.6
8/25/22	16:03:12	38.2775	-108.9136	-2.6150	4.1	-0.8		2.7
8/30/22	5:48:40	38.2693	-108.9368	-0.1100	1.6	0.1	0.6	4.7

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	*M_D*[4]	*M_W*[4]	Horizontal Distance from Injection Well (km)
9/4/22	7:37:21	38.2630	-108.8835	2.1800	-0.7	-0.1		3.9
9/5/22	22:12:45	38.2831	-108.9036	-2.2160	3.7	-0.2	0.7	1.7
9/6/22	15:09:38	38.2830	-108.9052	-1.9560	3.5	-0.3		1.7
9/8/22	6:17:33	38.3507	-108.9064	-3.4820	5.0	-0.4		6.1
9/9/22	5:18:45	38.2831	-108.9053	-1.9980	3.5	-0.4	0.8	1.7
9/12/22	12:17:50	38.4342	-108.5723	-3.2800	4.8	1.6		32.1
9/20/22	8:10:29	38.2792	-108.8972	-3.1670	4.7	0.2	0.9	1.9
9/23/22	19:31:08	38.2857	-108.9002	-1.9480	3.5	-0.5		1.3
9/24/22	11:56:49	38.2863	-108.8992	-1.8870	3.4	-0.4		1.2
9/28/22	0:05:06	38.3234	-108.9735	-2.4700	4.0	1.3	1.5	7.5
9/28/22	19:54:47	38.2861	-108.8985	-1.9360	3.5	-0.4	0.8	1.2
10/4/22	11:52:31	38.1868	-109.0360	-5.9500	7.5	0.6		17.3
10/4/22	22:34:50	38.2830	-108.9041	-2.2420	3.8	-0.6	1.2	1.7
10/4/22	22:34:57	38.2830	-108.9041	-2.2390	3.8	-0.8		1.7
10/5/22	1:00:26	38.2830	-108.9042	-2.2550	3.8	-0.2		1.7
10/5/22	1:00:56	38.2830	-108.9042	-2.2400	3.8	0.4	1.0	1.7
10/8/22	13:12:23	38.2777	-108.9205	-2.3780	3.9	-0.5	0.8	3.1
10/8/22	19:09:49	38.2830	-108.9047	-2.0790	3.6	-0.4		1.7
10/11/22	15:33:41	38.2751	-108.9028	-2.1950	3.7	-0.6		2.5
10/11/22	17:37:19	38.3430	-108.9878	-3.2830	4.8	0.0		9.6
10/13/22	21:45:01	38.2834	-108.9061	-1.8920	3.4	-0.2		1.8
10/17/22	9:18:18	38.2785	-108.9079	-2.4910	4.0	0.2	0.8	2.3
10/20/22	7:31:09	38.5605	-108.9913	-14.4800	16.0	0.5	1.2	30.5
10/20/22	7:31:38	38.5620	-108.9922	-14.7100	16.2	-0.5		30.7
10/20/22	7:31:54	38.5585	-108.9875	-14.4700	16.0	-0.7		30.2
10/25/22	4:40:44	38.2842	-108.9030	-1.9420	3.5	-0.1	0.7	1.5
10/28/22	10:02:57	38.2805	-108.9112	-1.9360	3.5	-0.2		2.3
10/29/22	4:51:59	38.2750	-108.8862	-0.9120	2.4	-0.7		2.5
11/4/22	12:28:37	38.2784	-108.9213	-2.1120	3.6	-0.5		3.1
11/4/22	13:38:00	38.2858	-108.8999	-1.9580	3.5	-0.8		1.3
11/5/22	17:00:09	38.2660	-108.8743	-0.1400	1.7	-0.1		3.8
11/7/22	8:56:25	38.4412	-108.9698	-4.0620	5.6	1.6	1.7	17.3
11/8/22	1:48:42	38.2835	-108.9048	-1.9390	3.5	0.1	1.0	1.7
11/15/22	16:14:00	38.2693	-108.8815	-1.5500	3.1	-0.3		3.2
11/18/22	8:01:08	38.2816	-108.9072	-2.1110	3.6	2.2	2.0	2.0
11/20/22	19:38:53	38.2812	-108.9070	-1.9640	3.5	-0.5		2.0
11/22/22	15:38:46	38.2824	-108.9054	-2.0440	3.6	-0.3		1.8
11/27/22	19:24:36	38.2630	-108.9452	-1.2500	2.8	-0.3		5.8
11/30/22	0:56:49	38.4039	-109.0079	-3.8580	5.4	1.1	1.4	15.5
11/30/22	9:54:35	38.2838	-108.9043	-1.9190	3.4	-0.6		1.6
12/1/22	21:55:28	38.2693	-108.9277	-0.6100	2.1	-0.5		4.2
12/3/22	8:34:34	38.2826	-108.9064	-1.9090	3.4	-0.1		1.8
12/3/22	10:02:39	38.2387	-108.7962	-5.8800	7.4	0.1		10.8
12/13/22	16:18:41	38.2825	-108.9060	-2.0000	3.5	-0.4		1.8
12/19/22	21:21:42	38.2837	-108.8963	-1.7410	3.3	-0.2		1.4
12/24/22	16:06:54	38.2755	-108.9179	-3.1200	4.6	-0.3		3.1
12/26/22	2:25:50	38.2826	-108.9063	-2.0110	3.5	0.1	0.8	1.8
12/26/22	7:03:04	38.2809	-108.9011	-2.8010	4.3	-0.4		1.8
12/26/22	11:07:06	38.2830	-108.9057	-2.0000	3.5	-0.6		1.8

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	M_D[4]	M_W[4]	Horizontal Distance from Injection Well (km)
12/26/22	21:14:44	38.2830	-108.9055	-2.0200	3.5	0.4	1.0	1.8
12/26/22	21:29:30	38.2830	-108.9054	-2.0220	3.5	0.0		1.8
12/27/22	4:58:00	38.2828	-108.9056	-2.0570	3.6	-0.1	0.6	1.8
12/27/22	4:59:05	38.4049	-108.9334	-4.3080	5.8	0.1		12.5
12/28/22	22:13:22	38.3526	-108.8813	-5.3360	6.9	-0.4		6.3
12/29/22	12:50:11	38.2828	-108.9063	-1.9890	3.5	-0.7		1.8
12/30/22	14:16:33	38.2832	-108.9049	-2.0160	3.5	0.2	0.9	1.7

[1] Date and time listed are in Coordinated Universal Time, UTC (Mountain Standard Time = UTC – 7 hours; Mountain Daylight Savings Time = UTC – 6 hours)
[2] Elevation is given with respect to mean sea level.
[3] Depth is referenced to the surveyed ground surface elevation at the injection wellhead, 1.524 km.
[4] M_D = duration magnitude; M_W = moment magnitude. All magnitudes computed using only PVSN data.